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CONIFEROUS TREES ASSOCIATED WITH INTERDUNE DEPOSITS IN THE JURASSIC NAVAJO SANDSTONE FORMATION, UTAH, USA

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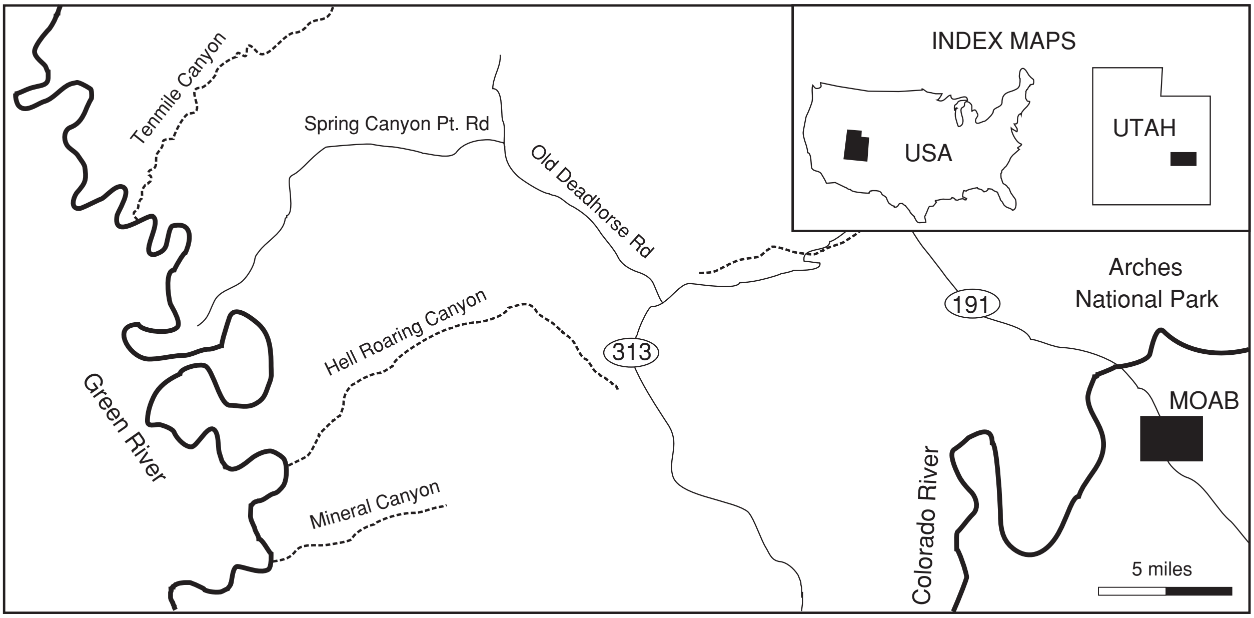
Abstract: The Lower Jurassic Navajo Sandstone Formation of south-west USA represents one of the largest erg deposits ever to have developed on Earth. Here, we report the widespread occurrence of silicified conifer stumps and trunks within interdune deposits near Moab, south-east Utah. Where present as (par)autochthonous assemblages, trees are associated with the deposits of spring-fed carbonate lakes. A few stumps preserved in growth position are rooted in aeolian sandstone immediately below the lake deposits, and evidently established on interdune soils in response to a rising water table. Following at least several decades of growth, trees were killed as the water table continued to rise forming shallow lakes containing ostracodes. Where present as allochthonous assemblages, randomly orientated tree trunks are associated with massive sandstone beds interpreted as fluidized mass flow deposits. These may have formed when dune slip-faces collapsed during occasional heavy downpours of rain, destroying stands of trees. The occurrence of large conifers over a wide area of the Navajo Sandstone Formation in south-east Utah may record long-lived pluvial episodes during which the dune field stabilized, or reflect the erg-margin position of the localities.

Key words: aeolian sandstone, Colorado Plateau, erg, Jurassic, sedimentology.

THE Lower Jurassic (Pliensbachian–Toarcian) Navajo Sandstone Formation and its lateral equivalents represent one of the largest erg (sand sea) deposits in Phanerozoic history, covering approximately 366,000 km^2 of the Colorado Plateau, south-east USA (Porter 1987; Kocurek 2003). Because of its great areal extent and the preserved size of its dune foreset beds (up to 30 m high), the Navajo Sandstone Formation is commonly regarded as the culmination of the long history of erg deposition on the Colorado Plateau, which commenced in the Pennsylvanian and ended in the Late Jurassic (Blakey *et al.* 1988; Peterson 1988). Implicit in this has been the perception that the Navajo Sandstone Formation represented the driest interval to affect this arid climatic zone (Parrish 1993*a*, *b*).

Previous studies of the Navajo Sandstone Formation have focused on aeolian sedimentology (e.g. Middleton and Blakey 1983; Herries 1993; Blakey 1996*a*) and its implications for understanding Early Jurassic atmospheric circulation (e.g. Marzolf 1983; Parrish and Peterson 1988; Loope *et al.* 2001, 2004). In contrast, widespread interdune deposits containing carbonate beds, although commonly noted, have rarely been described in detail (Gilland 1979; Bromley 1992; Eisenberg 2003). These are especially important because they contain fossil assemblages that shed significant light on enigmatic Navajo Sandstone Formation ecosystems (Winkler *et al.* 1991; Rinehart *et al.* 2000).

In this paper, carbonate-bearing interdune deposits with abundant fossil trees are described from localities near Moab, Utah; these have been only briefly noted in earlier literature (Loope 1979; Stokes 1991). Our report comprises a general reconnaissance study of the Jug Rock, Mineral Canyon, Dubinky Wash and Tenmile Point 7·5′ Quadrangles, and a more detailed study in the Tenmile Point Quadrangle located on the south side of Tenmile Canyon at the confluence of an unnamed canyon informally known as ‘Trough Canyon’ (Text-fig. 1). We withhold exact location details to protect the fossil trees from looting. Parties with valid scientific need will be provided with the information by one of us (JTP) on request.



TEXT-FIG. 1. Map of study area. Dashes indicate canyon drainage axes; paved highways and rivers are labelled. We intentionally omit the location of Trough Canyon to protect the fossil resources there.

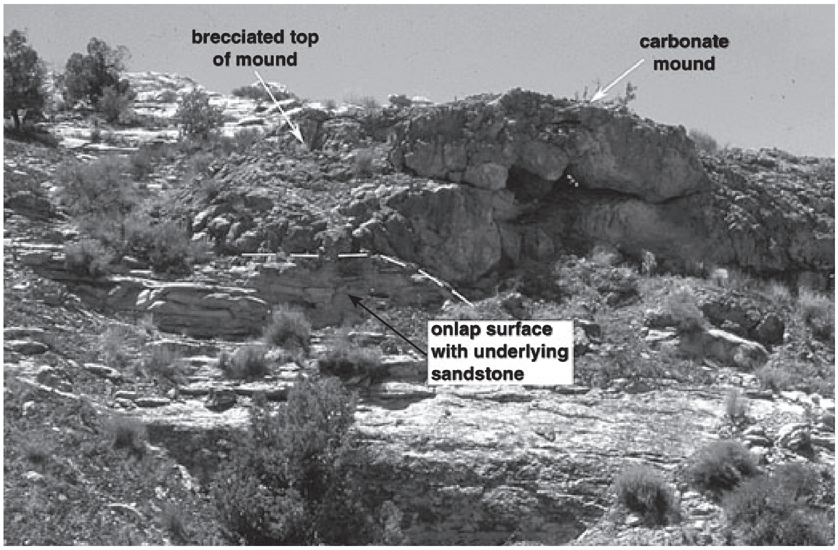
INTERDUNE DEPOSITS IN RECONNAISSANCE AREA

Throughout the reconnaissance area, the Navajo Sandstone Formation has a stratigraphic dip of 1–2 degrees north-west (Bates and Sable 1955) and is only 75–140 m thick (Hinze 1988), compared with 600–700 m thick in south-west Utah. Although aeolian sandstone units predominate, interdune strata are unusually common here (Verlander 1995*a*, *b*). Based on this evidence an erg margin setting has been inferred for south-east Utah (Bromley 1992; Herries 1993). Fossil trees occur at 17 (31 per cent) of 53 widely spaced interdune sites containing carbonate beds documented by F. A. Barnes (1993, pers. comm. 2001) over several decades of exploration. We visited eight of the tree-bearing localities in the course of this study. Here we describe the interdune facies most commonly associated with the fossil trees, which include carbonate mounds, flat-lying carbonate beds, vertically orientated zones of massive sandstone, and lenticular beds of massive sandstone.

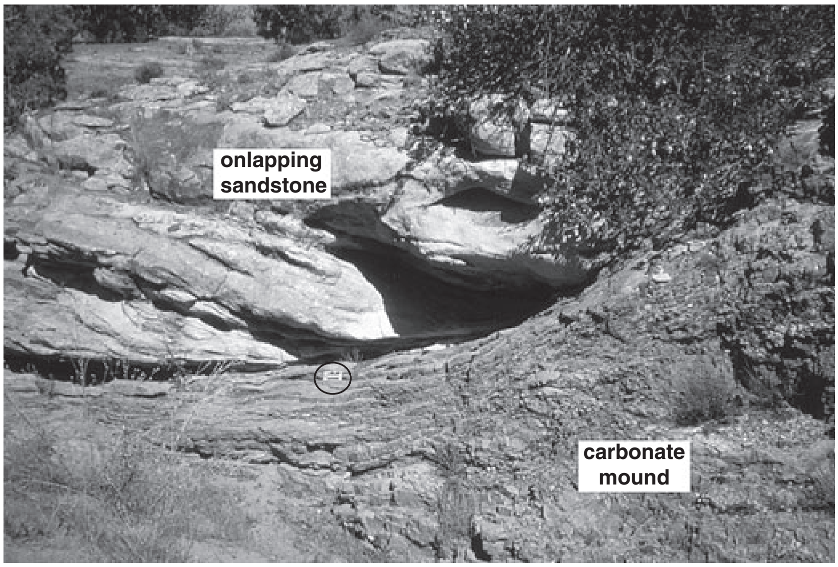
Carbonate mounds

Carbonate mounds, up to 2 m high and 6 m in diameter, are abundant in the Navajo Sandstone Formation in the reconnaissance area, and also occur near Dewey Bridge, about 33 km to the north-east. The mounds are generally distributed in clusters or lines, and rarely occur singly. Near Tenmile Canyon there is a cluster of three, very large mounds, and a line of mounds approximately 1·1 km long was also observed near Dewey Bridge. The mounds comprise highly vuggy carbonate that commonly contains crack fills with sparry calcite. The upper surfaces, particularly near the crests of the mounds, are brecciated. Where a mound has been partially eroded, leaving a cross-section, the interior is brecciated or contains a void (Text-fig. 2). The flanks of the mounds are commonly massive or laminated, dipping away from the central core. The carbonate mounds at Tenmile Canyon contain abundant chert, and a few of those at Dewey Bridge contain minor chert.

The underlying sandstone is visible at some carbonate mounds and is massive or contains aeolian stratification, but is typically carbonate-cemented. Overlying sandstone beds, where preserved, onlap against the mounds (Text-fig. 3). Some carbonate mounds are embedded within a laterally extensive, flat-lying carbonate bed (see below), whereas in most cases, the mounds appear to be isolated. In a few cases, lateral tracing of depositional surfaces shows that the mounds, in part, underlie these beds; the flat-lying carbonate beds onlap against the mounds and dip away from the central structure. A mound at Dewey Bridge, dissected by erosion, contains several such accretionary carbonate layers (Text-fig. 3). Given the onlapping relationship of carbonate beds in the fully exposed carbonate mounds, it is reasonable to suppose that



TEXT-FIG. 2. Large carbonate spring mound near Tenmile Canyon, dissected by erosion, looking south-south-west. Note the large vug in the centre of the mound, onlap of carbonate over sandstone at the base, and brecciated top. The mound is *c.* 2 m high.



TEXT-FIG. 3. Cross-section of large carbonate mound near Dewey Bridge showing onlapping of the adjacent sandstone. Note the accretionary layers in the carbonate mound dipping towards the left, away from the central vent, which is out of the picture to the right. This mound sits along a line of mounds, probably a carbonate fissure ridge; 10-cm scale just left of centre (ringed).

carbonate beds associated with apparently isolated mounds simply have not yet been exposed. However, in a few cases, genuinely isolated carbonate mounds may occur.

Flat-lying carbonate beds

The flat-lying carbonate beds, associated with the carbonate mounds, are generally < 1 m thick (always < 2 m thick), and comprise light grey to greyish black micrite, commonly with small-scale sparry calcite vugs (Text-fig. 4). Beds may be massive, show a thrombolitic texture, horizontal lamination, wavy lamination, or contain red siltstone and sandstone laminae. Other features are present but found at only one or two localities: 20-cm-thick beds exhibiting highly contorted, enterolithic lamination (*sensu* West 1975); tepee structures; desiccation cracks with upturned edges, crack-fills containing red siltstone and sandstone, and angular intraclasts up to 12 cm long; moulds of gypsum crystals, up to 2 cm in diameter, and putative halite pseudomorphs, in green/grey mudstone. Chert is present in the thickest (> 1 m) carbonate beds, and occurs as small, highly irregular nodules < 1–5 cm thick; continuous chert beds are rare. Fossil remains are limited to a few indeterminate ostracodes, algal or cyanobacterial filaments, and a possible charophyte observed in thin section; a single impression of an indeterminate conifer shoot with helically arranged, broad-based leaves discovered by Fran Barnes (pers. comm. 2001) similar to some extant Araucariaceae and Podocarpaceae; and abundant silicified tree-trunks (see below).

TEXT-FIG. 4. Photograph of a flat-lying carbonate bed; geological hammer (35 cm) for scale.

Massive cemented zones cross-cutting aeolian sandstone

Another feature seen in the reconnaissance area is vertically orientated zones of massive, carbonate-cemented sandstone, which locally crosscut otherwise undisturbed aeolian sandstone. The most spectacular such occurrence near Monitor Butte, in the Merrimac Butte 7·5′ Quadrangle, is approximately circular in plan view and 2 m in diameter. These commonly weather out as mounds, probably owing to the greater degree of carbonate cementation. The three-dimensional geometry of such cemented features is visible at only one locality, where the body under consideration is underlain by a narrow, vertically orientated zone of massive sandstone. The edge of the massive zone is characterized by centimetre-scale slumps and faults. Elsewhere, disruptions of normal aeolian sandstone that are funnel-shaped in cross-section appear to represent similar phenomena.

Non-aeolian sandstone beds

Two main types of non-aeolian sandstone beds were noted in the reconnaissance area. Most common are massive sandstone units, up to 17 m thick, which are lenticular or sheet-like in geometry. In several cases, these beds are traceable in outcrop for many tens of metres and locally wedge out against aeolian sandstone units. The massive beds are composed of very fine- to fine-grained quartz sandstone with a well-sorted, well-rounded texture, and the beds additionally contain common, metre-sized intraclasts of laminated carbonate. Some, though not all, such bodies may show a scoured base and contain large silicified tree-trunks (Text-fig. 5). The second type of non-aeolian sandstone is much rarer and comprises erosive-based beds that exhibit lateral accretion sets about 1·5 m high and 10 m wide, decimetre-scale trough cross-bedding, and basal accumulations of silicified fossil wood.

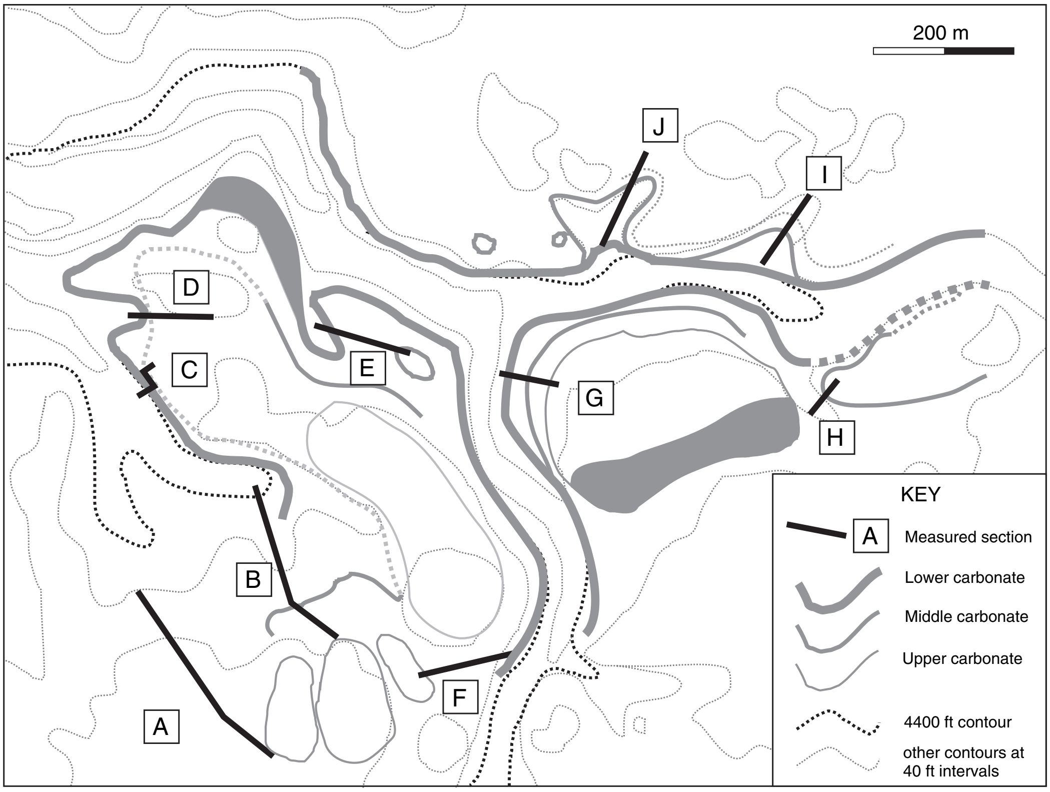
DETAILED STUDY OF THE 'TROUGH CANYON' AREA

To improve knowledge of the three-dimensional geometry of some of the facies described above, the rocks were mapped in the vicinity of a small, unnamed tributary of Tenmile Canyon, informally known as Trough Canyon (Text-fig. 6). Nine sections were measured (A–J) across the map area (*c.* 840 × 740 m) and correlated using flat-lying carbonate beds (Text-fig. 7). Three such carbonates were noted, and in the following description are termed the lower, middle, and upper carbonate beds.

The lower carbonate bed is a medium-grey unit showing horizontal or wavy lamination, and localized brecciation of the upper surface. It is up to 1·4 m thick near E and G but pinches out in all directions. Close to F in the southern part of the map area, it becomes progressively split by aeolian sandstone, whilst in the north-west part near D, it passes into red siltstone and fine-grained sandstone. In total, the unit covers an approximate area of $< 0{\cdot}65$ km^2. Over most of the map area, the lower carbonate bed is overlain by aeolian sandstone; however, near A–C and H massive sandstone containing silicified tree-trunks occurs in a SW–NE-orientated belt.

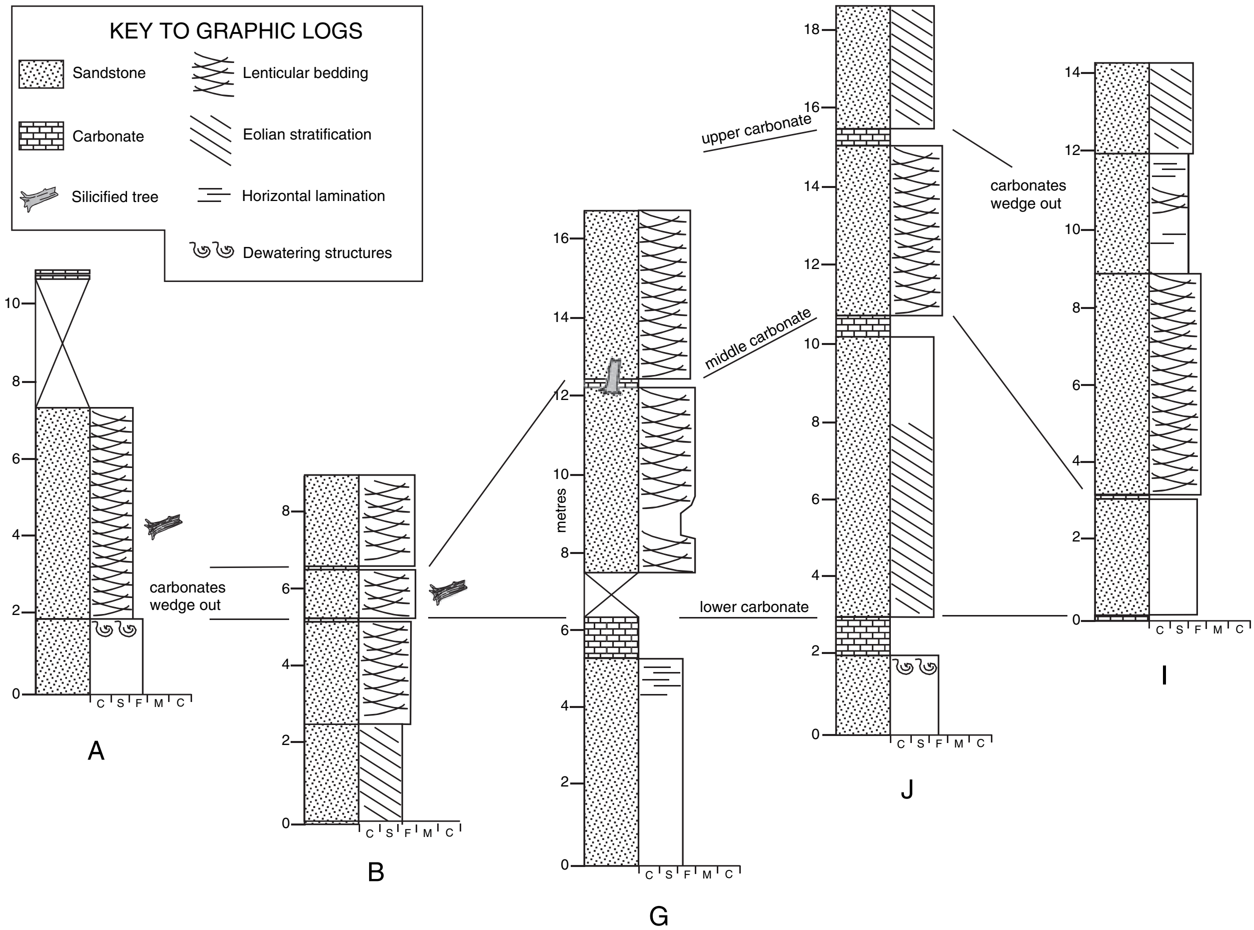
The middle carbonate bed drapes irregularly on the top of the underlying massive sandstone, including silicified trunks near C. It is up to 0·55 m thick near J, where it contains a cluster of carbonate mounds. Another cluster of large carbonate mounds occurs near H, and here it

TEXT-FIG. 5. Fossil trunks (arrows), subhorizontal to bedding, within a massive sandstone of lenticular geometry; uppermost trunk is 39 cm in diameter.



TEXT-FIG. 6. Geological map of the Trough Canyon area showing the mapped occurrence of carbonate beds. We withhold precise location details to protect the site from looting.

onlaps against one mound with an apparent dip of up to 26 degrees. The middle carbonate bed pinches out against aeolian sandstone near A and F. Although other lateral terminations cannot be observed, the unit has a probable area of $< 0{\cdot}25$ km^2. The middle carbonate bed is overlain by aeolian sandstone over much of the map area, but near B and G it merges with the upper carbonate bed, demonstrating that intervening aeolian strata represent an extensive split. The upper carbonate bed is up to 0·4 m thick, pinches out into red siltstone near I, and has a



TEXT-FIG. 7. Selected graphic logs through some of the interdune deposits at Trough Canyon showing carbonate beds wedging out into aeolian sandstone or interdune siltstone; see Text-figure 6 for location of the measured sections. Grain size key: C, clay; S, silt; F, fine sand; M, medium sand; C, coarse sand.

probable area of < 0·25 km^2. The stratal package comprising the middle and upper carbonate beds is disrupted by large-scale dewatering structures across much of the map area. These prominent early diagenetic features are not described here.

INTERPRETATION OF INTERDUNE DEPOSITS

Interdune facies containing carbonate beds similar to those described above have been widely noted in earlier literature on the Navajo Sandstone Formation (Gilland 1979; Middleton and Blakey 1983; Winkler *et al.* 1991; Bromley 1992; Desborough and Poole 1992; Herries 1993; Bryant 1997; Bryant *et al.* 1999; Eisenberg 2003). Here we provide a new palaeoenvironmental synthesis for interdune facies in our reconnaissance area where we relate them, in part, to the existence of a groundwater spring system.

Carbonate spring mounds

One of the most striking features of the interdune facies is the carbonate mounds. These could conceivably represent large stromatolites, as conjectured elsewhere in the Navajo Sandstone Formation (Eisenberg 2003). However, we consider this interpretation unlikely in the absence of widespread laminated and clotted microbial textures (Riding 2000), although we do not rule out the possibility that microbial mats may have contributed to mound growth. In our view, the carbonate mounds represent the non-biological precipitates of spring vents, i.e. carbonate spring mounds *sensu* Pentecost and Viles (1994). One of the key characteristics of the mounds is their localized linear distribution. This would be inexplicable if they are stromatolites but is readily explained if they are, in fact, spring vents as groundwater may have been focused along underlying structural lineaments. The carbonate mounds formed topographic highs in the interdune area as indicated by the onlapping geometry of overlying sandstone beds, and so differ, for example, from the Quaternary carbonate spring deposits in Lake Tecopa, California (USA), which show inflation of overlying beds and evidently grew in the subsurface (Nelson *et al.* 2001).

Flat-lying carbonate beds, laterally equivalent to, or onlapping against, the carbonate mounds are interpreted here as the deposits of shallow lakes that ponded within interdune depressions (Gilland 1979; Bromley 1992). Bed relationships suggest that in most cases carbonate mound growth pre-dated the deposition of the flat-lying carbonate beds and that therefore the springs were the probable source of water for the lakes; isolated carbonate mounds represent springs that did not develop lakes. Together with the brecciation of the upper surfaces of some carbonate mounds, these facts suggest that the mounds dominantly accumulated subaerially, further diminishing the likelihood that they are stromatolites.

Additional support for a spring origin for the carbonate mounds is provided by the presence of vertically orientated zones of massive carbonate-cemented sandstone, which record localized sediment liquefaction. In earlier literature, these 'sand boils' have commonly been interpreted as seismically induced features (Holzer and Clark 1993), but groundwater flows can generate similar structures (Li *et al.* 1996; Massari *et al.* 2001). In terms of their size and shape, the carbonate-cemented zones are very similar to structures seen in boiling (motion) springs, i.e. springs with vertical flow that is strong enough to keep the sand grains near the surface partially in suspension (Guhman and Pederson 1992). Our features cannot be directly related to the carbonate spring mounds discussed above although sandstone below such mounds is also typically carbonate-cemented. It is possible that the groundwater flow structures may represent deeper parts of the spring system, or alternatively feeders of carbonate-poor springs that did not develop spring mounds.

Consideration of the palaeogeographical setting of the Navajo Sandstone Formation (Riggs and Blakey 1993; Peterson 1994; Blakey 1996*b*) helps explain the existence of spring systems in this part of the erg. Although the topography was generally low-lying, as indicated by the continuous nature of many aeolian units, gradient increased towards the Uncompahgre Uplift, approximately 200 km to the east (Peterson 1988). Facies analysis strongly implies that the marked eastward thinning of the Navajo Sandstone Formation is partly depositional (Bromley 1992; Herries 1993; Verlander 1995*a*), and not primarily related to the J-2 unconformity surface that directly overlies the formation (Peterson and Pipiringos 1979). Assuming the existence of a lapout relationship with the Uncompahgre Uplift, even subtly, there would have been sufficient artesian head on the groundwater flow off the uplift zone to allow formation of the 2-m-high carbonate spring mounds observed. However, if the eastward thinning was entirely due to truncation, it may be impossible to delineate palaeohydrological flow, as the up-gradient portion of the formation would be missing.

Interdune carbonate lakes

The flat-lying carbonate beds are interpreted as spring-fed carbonate lakes. Mapping in the Trough Canyon area shows that these shallow, small (typically $< 0{\cdot}65\ km^2$) bodies of water were confined to interdune depressions. Periodically, the lakes completely dried out, as indicated by sediment-filled desiccation cracks and, in numerous places, abundant intraclasts and a surficial fabric consistent with subaerial weathering and the early stages of calcrete formation (e.g. Soreghan 1992). Quartz grains in many beds and interlamination with red siltstone indicate that winds strong enough to carry these grains into the lake persisted throughout deposition, and localized splits indicate that migrant aeolian dunes occasionally partially infilled these water bodies.

Micrite probably precipitated in lake surface waters in response to evaporation and/or microbial processes under a fairly arid climate. On occasion, salinity evidently became sufficiently elevated to precipitate gypsum and possibly halite. Locally, perhaps close to the lake margin, sediments may have been dominated by evaporites, as indicated by the occurrence of enterolithic texture at one locality; this feature forms by the repeated dehydration and hydration of massive gypsum, now replaced by calcite (West 1975). Fossil remains provide support for fluctuating salinity in the lakes, including both freshwater charophytes and euryhaline ostracodes. Large trees associated with the interdune lakes (see below) presumably required access to fresh groundwater for growth.

Mass flows and ephemeral bedload rivers

Non-aeolian sandstone bodies provide further information about the interdune environments associated with the spring-fed lakes. Earlier interpretations of massive sandstone in aeolian settings, similar to those seen in our area, have partly centred on bioturbation (e.g. Bigarella 1975; Plaziat and Mahmoudi 1990). In contrast, the lenticular bodies of massive sandstone described here are interpreted as mass flow deposits (cf. Herries 1993). This is based on their massive nature, channelled geometry that infill hollows between preserved aeolian dunes, and very large carbonate-suspended clasts. Given that cohesionless aeolian sand was the main material available for transport, the sediment must have moved as a fluidized mass flow, buoyed up by high pore pressure (Boggs 2001). Mass flow deposits possibly resulted from heavy downpours of rain or seismic events, which led to the sudden collapse of dune slip-faces and destruction of stands of interdune trees, similar to events documented elsewhere in the geological record (Loope and Mason 1999).

In contrast, the much rarer occurrence of trough cross-bedded sandstone beds with lateral accretion structures are interpreted as deposits of ephemeral, sinuous streams, which reworked loose aeolian sand into channel-forms before being absorbed back into the porous sediment (Boggs 2001). Some are associated with the tops of the massive sandstone deposits and may have resulted from surface run-off following water expulsion from fluidized-flow events, whereas others were probably formed by groundwater sapping (Luo *et al.* 1997) or as the direct product of heavy monsoonal rains (Loope *et al.* 2001, 2004).

FOSSIL TREES

The silicified trees were studied to improve knowledge of the ecology of the wet interdune deposits described above. They were studied in their facies context and wood was collected for further analysis. In total, 15 wood specimens from all eight interdune sites were collected and thin sectioned, including those from both lake and mass flow assemblages. Thin sections were prepared along transverse (TS), radial longitudinal (RLS) and tangential longitudinal (TLS) sections. These samples are stored and curated in the Geology Museum of the University of Bristol, Earth Science Department, UK (accession numbers BRSUG 28514–28528).

Tree architecture

Based on external morphological features, fossil remains include roots, stumps, and the upper parts of trunks (Text-fig. 8). Most common are the trunk fragments, up to 93 cm in diameter and 2·9 m long, which locally exhibit common, oval, irregularly arranged branch scars, although no lateral branches were observed. Much less common are the stump fragments, which are recognized by flaring in diameter at one end of the trunk, and transverse compression bands. Rare fragments interpreted as root remains comprise irregular, knotty material showing twisting of the wood structure.

The specimens that represent stumps and trunks have diameters ranging from 10 to 93 cm ($n = 37$; modal class, 15–20 cm; mean, 30·19 cm; Text-fig. 9). Niklas (1994) derived the following equation for estimating tree height from trunk diameter for woody plants, based on empirical biomechanical data:

$$\log_{10}H = 1{\cdot}59 + 0{\cdot}39(\log_{10}D) - 0{\cdot}18(\log_{10}D)^2$$

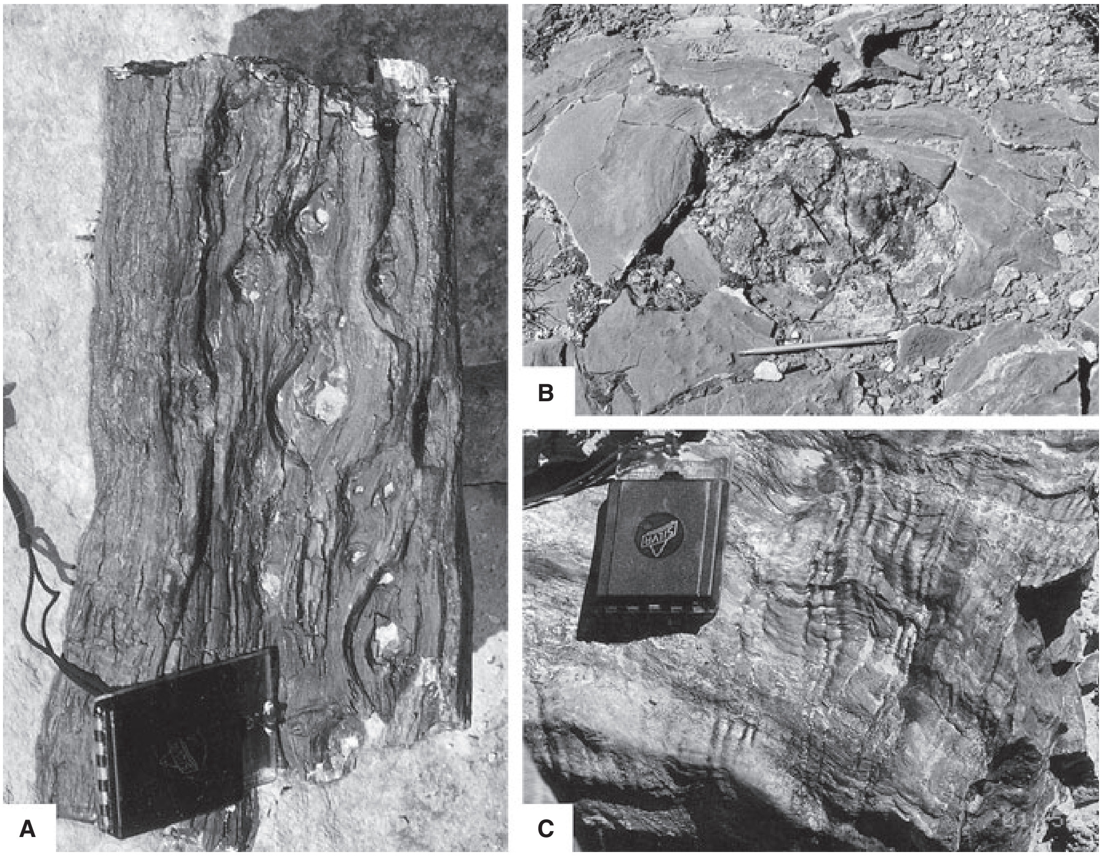
where H is estimated tree height and D is maximum diameter of the trunk. Putting our observed trunk diameters into this equation suggests that tree height ranged from 10·47 m ($D = 10$ cm) to 37·83 m ($D = 93$ cm), with a mean height of 21·80 m ($D = 30{\cdot}19$ cm). As the measured trunks were not completely preserved in cross-section, and because there is no way of knowing whether they represent the widest part of the trunk (except in the case of rare stump material), the above values underestimate tree height. We provide these calculations merely to emphasize that these were large trees.

Fossil wood systematics

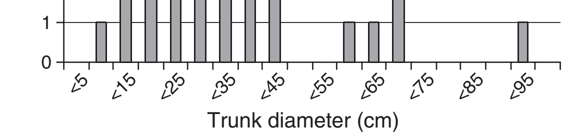
Despite their well-preserved external morphology, the preservation of wood anatomy is typically extremely poor. Although the gross structure of the tracheid cells is always preserved, parenchymatous ray cells and all types of subcellular ornamentation are preserved only very rarely. In addition, almost no colour contrast exists between silica infilling the cell lumina and silica replacing the wood tissue, further hindering observation and illustration; this may be related to subaerial oxidation under ancient or present-day arid conditions, but represents a common problem for studies of silicified wood (Bartholomew *et al.* 1970).

Despite this generally poor preservation, it is evident that all specimens are composed of pycnoxylic wood and probably represent a single morphotaxon with the following characteristics (Text-fig. 10). In RLS, tracheids exhibit uniseriate bordered pits. Pits are generally very poorly preserved, but appear to be typically spaced and circular, or contiguous and vertically flattened. Rays are parenchymatous and exhibit one (rarely two) large, circular cross-field pits of indeterminate type. In TLS, rays are uniseriate and 1–19 cells high ($n = 50$). Prominent tracheid septa are visible in both longitudinal sections. In TS, rays occur with a mean abundance of 4·3 rays per mm ($n = 50$). Resin ducts are unequivocally absent. Tracheids typically have a circular cross-sectional shape and commonly do not perfectly tessellate, leaving small triangular gaps. Although tracheids show some fluctuation in diameter (23–53 μm; $n = 500$), growth rings are absent in all specimens across tens of centimetres (Text-fig. 11).

Pycnoxylic woods of Mesozoic age are usually assigned to the Coniferales, although the Ginkgoales and a few extinct gymnosperm orders also exhibit a similarly compact structure (Stewart and Rothwell 1993). In the absence of well-preserved cross-field pits, our woods are



TEXT-FIG. 8. Fossil trees. A, upper trunk fragment showing branch scars. B, upright stump inferred to be in growth position surrounded by an accretionary rim of carbonate. C, transverse compression banding suggestive of basal stump wood. Clinometer (length 12 cm) and pencil (17 cm) for scale.



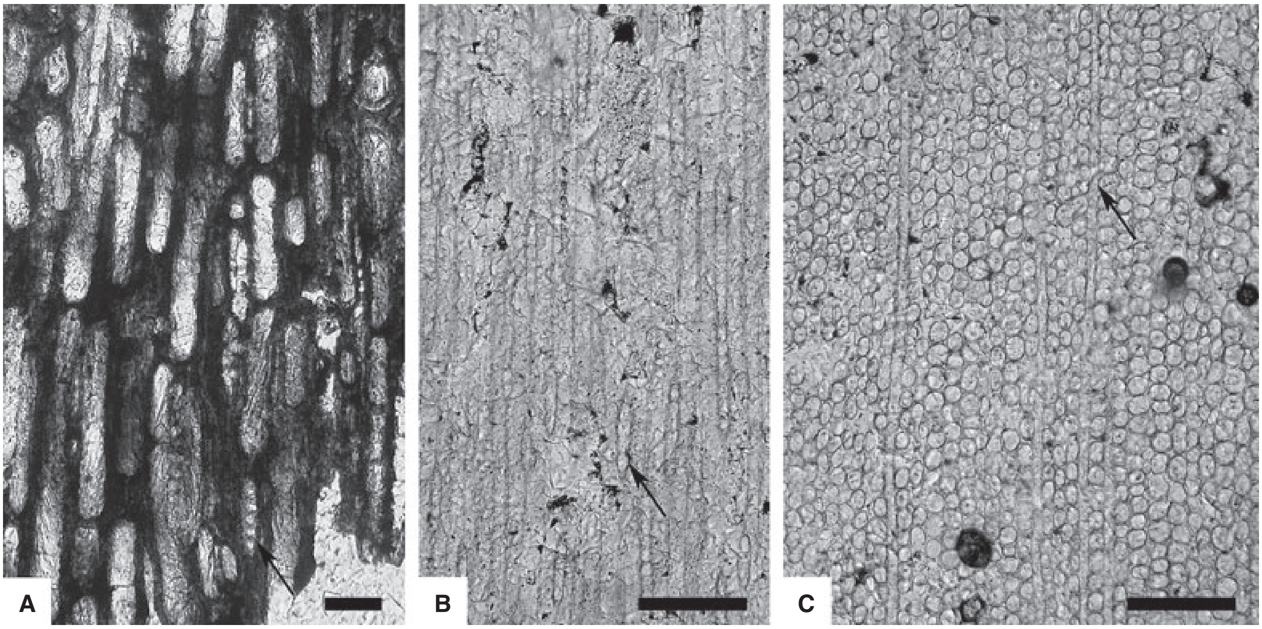
TEXT-FIG. 9. Histogram showing size-class distribution of silicified trunk diameters.

unidentifiable using the key of Kräusel (1949). However, we know of only two Jurassic wood morphotaxa characterized by tracheid septae of the kind seen in our material; these are *Xenoxylon* and *Metapodocarpoxylon* (Philippe and Thevenard 1996; Bamford *et al*. 2002). Our woods are similar to *Xenoxylon morrisonense* Medlyn and Tidwell, 1975 from the Upper Jurassic Morrison Formation of Utah, but can be assigned to *Xenoxylon* only with reservation. Owing to poor preservation, we cannot prove diagnostic features such as cross-field pit type or the dominant occurrence of vertically flattened tracheid pitting (Müller-Stoll and Schultze-Motel 1988).

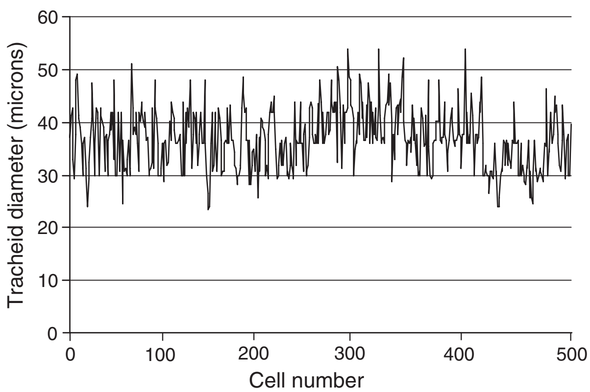
The phylogenetic position of trees with *Xenoxylon* wood is poorly understood. The morphogenus shares several characteristics with woods of the Araucariaceae and Podocarpaceae, i.e. those extant conifer families considered primitive in phylogenetic studies (Philippe and Thevenard 1996; Bamford *et al*. 2002), but does not fit comfortably into any extant family. Most likely it represents the wood of some extinct basal branch of the Coniferales (e.g. the Protopinaceae), or possibly even a different extinct gymnosperm order (Müller-Stoll 1987).

Tree taphonomy

As noted above, the fossil trees are associated with both lake carbonate beds and mass flow sandstone beds. In the



TEXT-FIG. 10. Fossil wood anatomy; all images from BRSUG 28514. A, tracheids showing uniseriate bordered pits (arrow) and septa, RLS. B, poorly preserved rays (arrow), TLS. C, absence of growth rings in TS; note the rays (arrow) and circular tracheids in cross-section, TS. Scale bars represent 25 μm in A and 50 μm in B–C.



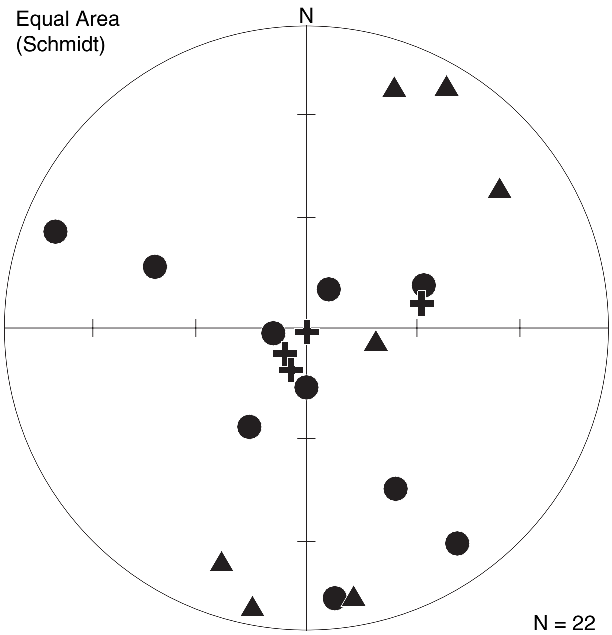
TEXT-FIG. 11. Graph showing the variation in tracheid diameter along a *c.* 2-cm radial transect. No growth rings are evident.

case of the carbonate beds, two modes of occurrence are observed. The first and most common assemblage comprises subhorizontal trunks positioned either immediately beneath a carbonate bed, so that the carbonate wraps directly over the top ($n = 43$), or actually contained within the carbonate bed itself ($n = 6$). The second mode of occurrence is as vertically orientated tree stumps ($n = 3$; Text-fig. 8). The stumps themselves typically protrude up through the upper bedding surface of the carbonate bed and are surrounded by a concentric, raised carbonate rim. Two of the upright stumps exhibit a pronounced cross-sectional asymmetry, with the location of the pith skewed to one side. The sandstone beneath the stump bases may be locally silty, but more typically is free of fine-grained sediment, consisting of friable, massive sandstone. Sandstone within 1 m below the friable sandstone commonly shows little disturbance of aeolian sedimentary structures other than slight rhizoturbation. Silicified roots were noted in the sandstone only at one locality, where their relationship with the overlying limestone or any vertical trunk could not be determined. Rare rhizoconcretions also occur near the base of one carbonate beds.

Tree-trunk fragments are also abundantly preserved within the mass flow sandstone beds. Trunks are by far the most common close to the top of these massive units although vertical distribution could only be judged for two massive beds. In places, trunks occur with high spatial density. Although the angle of dip of the long-axis of the largest trunks may vary greatly from near horizontal (7°) to near vertical (89°) within individual sandstone bodies, there is a moderate preferred orientation in long-axis direction of the trunks. In one bed, trunks are aligned in a dominantly NNE–SSW orientation ($n = 6$), whereas in a second bed at another locality, trunks exhibit a dominantly NW–SE orientation ($n = 10$; Text-fig. 12).

PALAEOECOLOGICAL SYNTHESIS

Data summarized above show that coniferous trees, some quite large, occasionally colonized interdune environments in the Navajo Sandstone erg. The few vertically orientated trees within carbonate beds are almost certainly



TEXT-FIG. 12. Stereonet showing the orientation of NW–SE- and NNE–SSW-trending silicified trunks within three massive sandstone beds (circles, triangles, crosses) interpreted as liquefied-flow deposits.

in growth position. The facies context of these stumps together with rare silicified roots in sandstone directly below the carbonate beds show that the trees established on sandy interdune soils in response to rising water table, but prior to lake formation. In fact, as carbonate is undisturbed around the stumps, the trees had apparently reached maturity before the onset of lake sedimentation. It is not envisaged that trees grew within the periodically saline lakes that developed later, but rather they were supplied by fresh groundwater. The only evidence for tree growth coincident with the existence of the lakes is the presence of rare rhizoconcretions near the base of a carbonate bed at one locality. The absence of pedogenic alteration apart from subtle rhizoturbation indicates that the sandy soils on which the trees grew were very immature, or at least composed of parent material (quartz sandstone) that did not readily develop a pedogenic fabric (USDA Soil Survey Staff 1999).

The more abundant prone tree-trunk material found within the flat-lying carbonate beds is almost certainly parautochthonous given the low-energy, confined lake setting envisaged. The dominant occurrence of tree-trunks near the bases of the carbonate beds lends further weight to the interpretation that trees colonized the area as the water table began to rise but prior to the onset of carbonate sedimentation. The small number of trunks that are enclosed within carbonate are interpreted to be the remains of trees that later rotted at the water line and toppled into the lake.

Other trees preserved in massive sandstone beds are allochthonous, and were evidently destroyed by mass flows that occasionally overwhelmed interdune stands. These trees became entrained in the mass flows with their long-axis orientations approximately parallel to the transport pathway. At one locality, some of the fossil trunks in massive sandstone are directly overlain by a carbonate bed. However, this assemblage is distinguished from trunks that are actually encased in carbonate (discussed above) and evidently represents a surface lag on the catastrophically reworked sandstone that subsequently became draped by carbonate sedimentation.

Growth conditions

More detailed information about tree growth in the interdune environments can be gained from analysis of wood anatomical and morphological features. Collectively these data support the lithofacies evidence, and suggest that growth occurred in waterlogged soils when the water table was close to, or at, the surface. For example, circular tracheids with intercellular spaces seen in our woods are an anatomical feature associated with stimulated ethylene production in waterlogged conditions (Yamamoto 1992). Furthermore, extreme asymmetry seen in two complete autochthonous stumps suggests that the trees tilted as they grew, requiring significant corrective buttressing. This, together with their shallow rooting systems, provides additional evidence for growth in loose, waterlogged soils (Kozlowski 1984) in which it was difficult to achieve firm anchoring.

The absence of growth rings in the wood of the 15 sampled trunks further indicates that there was little or no seasonal variation in temperature or water supply throughout the year capable of inducing cambial dormancy (Creber and Chaloner 1984). Given the palaeotropical setting (Smith *et al.* 1994), absence of significant temperature fluctuation is not surprising. However, in the light of the strongly monsoonal rainfall regime inferred for the region based on sedimentary data (Chandler *et al.* 1992; Parrish 1993*b*; Loope *et al.* 2001, 2004), the absence of drought-induced growth rings is striking; tropical conifers growing in such settings today commonly produce growth rings (Ash 1983; Jacoby 1989; Schweingruber 1992). However, assuming the trees grew in waterlogged soils, it is possible that they may have been buffered from seasonal variations in rainfall (Demko *et al.* 1998). In addition, growth under elevated atmospheric CO_2 levels (Berner 1994; Retallack 2001) may have significantly increased water-use efficiency (Beerling 1998) such that the trees were less drought sensitive.

The absence of growth rings in our woods creates difficulties for estimating the age of the largest trees. Modern temperate conifers have maximum growth-ring widths of 3·9 mm/year (Falcon-Lang 2005), but annual growth increments for tropical conifers are less well constrained as rings are not clearly formed in humid settings. However, maximum growth rates of less than 10 mm/year are probable (Creber and Chaloner 1984), and elevated atmospheric CO_2 levels are unlikely to have significantly augmented this value (Pritchard *et al.* 1999). Assuming a maximum annual diameter increase of 2 cm, the largest diameter tree (93 cm) would have had a minimum age of about 45 years.

Taphonomic biases

Although we only have evidence for trees associated with interdune environments that developed spring-fed lakes or were catastrophically buried by mass flows, it is possible that vegetation also grew elsewhere in the erg. The association of trunks with carbonate and massive sandstone beds might be a taphonomic artefact as trees that were not quickly buried in waterlogged sediments might simply have oxidized away. The only evidence for tree growth at drier sites might be rhizoturbation of sandy soils. The weathered surfaces of some aeolian sandstone beds that are not associated with carbonate beds appear to have a texture consistent with rhizoturbation, and possibly supported trees. However, the extreme homogeneity of the grains makes clear visualization of this texture difficult. The most that can be said is that this texture resembles that of the structureless sandstone that commonly occurs directly below carbonate beds with autochthonous trees. The occurrence of trunks in mass flow- and stream-deposited sandstone at intervals lacking any evidence of carbonate beds also supports the hypothesis of more widespread tree growth.

Palaeoenvironmental implications

The wider palaeoenvironmental significance of the spring-fed interdune lakes, mass flow deposits and large coniferous trees documented here is difficult to assess. These wet interdune deposits may reflect a geographical position on the erg margin (Verlander 1995*a*), or record long-lived pluvial episodes related to the varying strength of the Pangean megamonsoon (Loope and Rowe 2003; Loope *et al.* 2004). Clearly a more detailed study of their stratigraphic distribution is required to confirm which of these factors was of greatest importance. However, the existence of decadal climatic oscillations inferred from dune foreset analysis may favour the latter hypothesis (Chan and Archer 1999). Phenomena similar to those documented here are associated with pluvial events in Pleistocene and Recent deposits in the Sahara (Wendorf *et al.* 1994) and Egyptian Western Desert (Crombie *et al.* 1997). In these and other cases, spring mounds reflect the response of the groundwater system to wet episodes in an otherwise generally arid climate zone (Nelson *et al.* 2001).

Whether indicative of palaeogeographical position, pluvial episodes or a combination of both factors, the wet interdune deposits at many sites in the Navajo Sandstone Formation show that, at times, the largest erg to develop in the Earth's history supported highly productive but localized communities (Winkler *et al.* 1991). Elsewhere in the region, the Navajo Sandstone Formation contains skeletal remains of unionid bivalves (Bromley 1992), ostracodes, conchostracans, crocodylomorphs and dinosaurs (Rinehart *et al.* 2000), as well as a rich vertebrate and invertebrate trackway record (Brady 1960; Barnes 1993). This is in contrast to most deposits in the formation, which are barren. The wet interdune deposits probably represent partially connected networks of oases as seen in many modern deserts. However, modern examples of oases, in contrast to our Jurassic case study, are dominated by palms.

CONCLUSIONS

Clusters of large coniferous trees are reported from the Lower Jurassic Navajo Sandstone Formation of Utah, south-west USA, strata that possibly represent the largest erg (sand sea) ever to develop in Phanerozoic history.

Where preserved in growth position, the conifers are associated with carbonate beds, which formed in shallow spring-fed lakes ponded between aeolian dunes. Where preserved in allochtonous assemblages, trunks occur in massive sandstone beds interpreted as dune collapse deposits, which periodically destroyed interdune stands.

The fossil assemblages are interpreted as localized oases. Their occurrence over a wide area of Early Jurassic desert implies long-lived pluvial episodes during which the erg stabilized, or may reflect the erg-margin location of the study sites.

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