ADHESION STRUCTURES

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ABSTRACT: Adhesion structures form by the adhering of dry, wind-blown sand to a wet or damp surface. In plan-view morphology and internal structure (in parentheses), three adhesion structures occur: adhesion ripples (climbing-adhesion-ripple structures), adhesion warts (adhesion-wart structures), and adhesion plane bed (adhesion laminations). Related adhesion features are evaporitic-adhesion structures formed with surface salt growth. Experimental growth of adhesion structures in a wind tunnel shows that these types result from subtly different environmental factors; this enhances the value of adhesion structures as tools for detailed paleoenvironmental interpretations. The environmental factors involved are water content, wind direction variability, depositional surface condition, and the impact angle of saltating grains—a function of local depositional surface slope and wind velocity. The Cambrian Galesville Sandstone, Wisconsin, shows an abundance of adhesion structures; this allows for the recognition of repetitive sequences resulting from the lateral migration of eolian dunes, interdune areas, and marine environments. Adhesion structures also occur in the Ordovician St. Peter Sandstone, Wisconsin, indicating that parts of this enigmatic formation were deposited subaerially.

INTRODUCTION

Adhesion structures form by the adhering of dry, wind-blown sand to a wet or damp surface. Van Straaten (1953) first described such structures and referred to them as “anti-ripples.” Reineck (1955) was first, however, to document their formation, both experimentally and in nature. He recognized two distinctive forms, adhesion ripples (haftrippeln) and adhesion warts (haftwarzen). Hunter (1969) described adhesion ripples (“eolian microridges”) from modern beaches and presented the first possible ancient example. Hunter (1973) emphasized that adhesion ripples migrate upwind with deposition and climb over each other, producing a “pseudo-crosslamination.” Glennie (1970, 1972), Nagtegaal (1973), and Glennie and others (1978) described and illustrated from both modern sabkhas and the Permian Rotliegendes, northwestern Europe, numerous examples of wavy laminations, which they referred to as adhesion-ripple structures. Adams and Patton (1979) and Clemmensen (1979) interpreted wavy laminations as adhesion-ripple structures based on similarities with structures illustrated by Glennie (1970). Hobday and Jackson (1979, Fig. 11, p. 155) noted adhesion-ripple structures in the Pleistocene of Zululand, South Africa. Adhesion-ripple structures have been recognized in the Pleistocene of the Oregon coast (Hunter, 1980a), the Permian Toroweap Formation, Arizona (Hunter, 1981), and in modern interdune areas (Kocurek, 1981) and their ancient deposits (Mader, 1982). McKee (1982) has noted adhesion features from the Namib Desert, South West Africa, which were earlier described by Nagtegaal (1973).

Hunter (1980b) recognized an additional adhesion structure, termed by him “quasi-planar adhesion stratification.” Kocurek (1981) independently identified Hunter’s new adhesion structure and referred to it as “adhesion lamination.”

The different types of adhesion structures are morphologically distinct and, although sharing the same basic origin, each type reflects slightly different, rather specific depo-
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Fig. 2.—Epoxy peel made from modern interdune area deposits on Padre Island, south Texas, showing two generations of adhesion ripple pseudo-cross-laminations (indicated by arrows) overlain by adhesion laminations. Wind was from the left.

set. In a cross section perpendicular to the wind direction (or parallel to the crests of the adhesion ripples), the "foreset" laminations appear subhorizontal (Fig. 1). In our experience, once the eye is attuned to this structure, it is thereafter easily recognized. Interestingly, the climbing aspect of accreting adhesion ripples is apparent in Reineck's original figures (1955, Fig. 8, p. 357) but is not obvious. Reineck's introduction of artificially stained grains periodically during his experiments very clearly marked depositional surfaces and outlined the form of individual adhesion ripples but also tended to obscure translatent strata.

Adhesion warts were distinguished from adhesion ripples by Reineck (1955) by their irregularity and by the open-arched nature of adhesion-wart structures (Fig. 1). Adhesion warts are essentially small domes or oval bumps. They tend to have a more random distribution than adhesion ripples. Small adhesion warts, as well as adhesion ripples, may resemble rain-impact "ripples" described by Clifton (1977), but the latter are strictly a surface feature.

Reineck (1955) developed adhesion warts in strong winds with frequently shifting directions, thereby preventing the adhesion structures from accreting in any one particular direction. This favored upward rather than lateral accretion and domal forms resulted. Adhesion-wart accretion is, therefore, distinct from that of adhesion-ripple accretion, which occurs laterally into the wind with an upward climbing component at an angle to the depositional surface.

Adhesion plane bed forms by a "fly-paper phenomenon"—grains adhere to a damp surface not marked by adhesion ripples or adhesion warts. The bed is generally smooth, with irregularities not much larger than grain roughness. Adhesion laminations are faint, crinkly, and only a single-grain to a few millimeters thick (Figs. 1 and 2). In our experience, adhesion laminations are the most difficult adhesion structure to identify with certainty. They are, however, distinct from other parallel-laminated deposits because of the extreme thinness, faintness, and crinkly appearance of the laminae. This crinkly appearance reflects grain adhesion to the slight roughness of the depositional surface.

Evaporitic-adhesion structures (our term) are the features Nagtegaal (1973) and McKee (1982) described from the Namib Desert. Other authors have noted the wavy laminations associated with those structures and interpreted similar wavy laminae elsewhere as the same structure, referring to it as "adhesion ripples." In these examples, however, the irregular morphology, large size (up to a few centimeters), and internal structure are clearly not those of adhesion-ripple structures. In addition, their origin and relationship to evaporites disassociates them from typical adhesion structures, and we feel they are best treated as a separate phenomenon.

According to Nagtegaal (1973), the adhesion process in evaporitic-adhesion structures is by the hygroscopic action of evaporite nodules or cements. On the coast of the Namib Desert, when relative humidity is low, such as in the windy afternoon, the evaporitic-adhesion structures are hard, cemented by halite. No adhesion is then occurring and the wind may erode the structures into elongate forms. During this period, the wind may also deposit sand evenly over the sabkha surface, covering the evaporitic-adhesion structures. During periods of high relative humidity, typically in the morning and night, the evaporitic-adhesion structures become moist and soft. A portion of the loose dry sand deposited during the previous afternoon adheres to the new soft structures. This periphery of sand becomes newly incorporated rinds on the evaporitic-adhesion structures as they harden during the next after-
noon. These structures, therefore, accrete successive rims, producing a dome-shaped internal structure. Significantly, the deposition of dry sand and the adhesion of this sand occur in separate episodes, unlike the other adhesion structures where the two processes occur simultaneously. Conceivably, however, deposition and adhesion could occur at the same time with sand transport during periods of high relative humidity.

Sedimentation around evaporitic-adhesion structures and partial collapse with burial or dissolution of the salts produce an irregular, wavy bedding (see Nagtegaal, 1973, Fig. 2A, p. 9). Ahlbrandt and Fryberger (1981) described features from Sabkha Ar Riyas, Saudi Arabia (Fig. 14A, p. 309) that are salt-encrusted, very irregular, with a relief of 1 to 5 cm. Trenches showed discontinuous, wavy, nonparallel laminae. Fryberger (pers. comm., 1982) believes that these are also a salt structure. We have found apparently identical structures on the tidal flats of the eastern Colorado River delta in Sonora. Here these structures occur on halite-encrusted muddy portions of the delta and they grade southward into low, hollow domes a few centimeters in diameter on the sandy tidal flats. Eolian infill around these features and collapse of the features themselves produce very wavy, irregular laminations. These features, however, proved to be very rich in algal and bacterial filaments, and it remains unclear to us the relative roles organic binding and gas-doming versus evaporite growth and adhesion have in the formation of these structures. We believe it is important, however, to emphasize that eolian interdunes and sabkha areas are characterized by a variety of wavy, irregular laminations of several origins (see Hunter, 1981; Kocurek, 1981) and that caution must be used before equating interdune or sabkha wavy laminae to evaporitic-adhesion structures. True adhesion warts, algal mats, eroded microtopography, brecciated rain- or dew-formed crusts, fluid- or gas-blistered surfaces, and probably several other features also are conducive to the development of internal, wavy laminations with eolian or other sedimentation around the low, irregular positive surface features.

EXPERIMENTAL GROWTH OF ADHESION STRUCTURES: FACTORS AFFECTING MORPHOLOGY

Methodology

Our premise is simple: if the different types of adhesion structures all form by the same basic adhesion process, then their morphological distinctions must be the result of very subtle differences in environmental factors. We sought to determine these factors experimentally within a wind tunnel. Experiments were performed using the 6-m-long, variable-wind-speed tunnel at Augustana College (Rock Island, Illinois). Fine- to medium-grained sand was supplied at the upwind sediment-feed, the grains being allowed to saltate or creep the length of the tunnel. A containerized depositional area was maintained at the downwind end of the tunnel, with water content controlled by a series of capillary feeder tubes. Varying wind directions were simulated by rotating the container; slope was varied by tilting it. Factors tested included water content, sediment supply rate, relative wind velocity, wind direction variability, saltating grain impact angle (by changes in slope and velocity), and pre-existing surface relief. Important depositional factors and the resulting adhesion structures are summarized in Figure 3. Evaporitic-adhesion structures and related features were beyond the experimental scope of this study and are not addressed here.

Adhesion Ripples

Instantaneous formation of adhesion ripples occurred on surfaces as they emerged from an initial pool of water being bombarded by saltating grains (Fig. 4A). Where the depositional surface was smooth and covered with a film of water, wind stress produced wrinkle marks ("runzelmarken" of Reineck, 1969). These tiny ridges served as the first emergent projections upon which adhesion-ripple growth began. On depositional surfaces marked by pre-existing irregularities, adhesion-ripple

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Fig. 3.—Summary chart of the relationships discussed in detail in the text between depositional factors and adhesion structures. Thickness of the adhesion-structure deposits is proportional to their rate of accumulation. Double-barbed arrows (→) indicate wind direction; single-barbed arrows (←) and dotted lines indicate saltating grain impact paths. Diagonal lines dividing some rectangles separate alternate structures that may form, depending upon the other variable indicated. The very broad arrows shown in two cases indicate a continuum between two features.
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Adhesion-ripple growth began on emergent points of relief but proceeded independently of small irregularities as soon as overall emergence occurred. Larger irregularities, of course, provided sand shadow zones shielded from the impact of saltating grains, thereby preventing the formation of adhesion ripples. Our initial adhesion ripples, formed on the rhythmically spaced wrinkle marks, were highly regular and reflect a situation in nature wherein adhesion ripples form on an emerging surface under wind shear stress. In contrast, Reineck (1955) reported that his initial experimentally grown adhesion ripples were rather random in distribution and became more rhythmically spaced with time, more closely simulating a situation in nature wherein adhesion ripples form on a wet but not newly emergent surface. Reineck (1955) correctly stressed the sand-shadow effect in explaining why adhesion ripples tend to become evenly spaced. Each adhesion ripple shields an immediate downwind zone from saltating grains. Lateral growth is thereby also favored, and with time, many small disconnected adhesion ripples are replaced by fewer, larger, more continuous adhesion ripple ridges (Fig. 4B).

Adhesion-ripple growth was accompanied by climbing, and pseudo-cross-lamination could be seen forming along the glass sides of the wind tunnel (Fig. 5). Near maximum water content, adhesion ripples trap nearly all the sand grains that strike the surface. These adhesion ripples, therefore, must form in direct proximity to a dry sand source. Adhesion-ripple growth can be very rapid, for several centimeters of cross-sectional thickness were deposited in just a few minutes. Indeed, as long as sufficient water was supplied for capillary action, sand supplied at reasonable rates was...
incorporated into the growing climbing-adhesion-ripple structures. The most delicate building of adhesion ripples occurred, however, at low rates of sand supply. It seems apparent that as long as water and sand supply are maintained in balance, deposits of climbing-adhesion-ripple structures can increase in thickness indefinitely. Termination of capillary moisture, followed by its reinitiation, produced "bedding plane disconformities" between sets of climbing-adhesion-ripple structures (Fig. 5).

Moisture content exerted a strong control over adhesion-structure morphology. Adhesion-ripple growth occurred over a surprisingly narrow range of water contents, beginning on a totally saturated, just emergent surface and ending when saturation level fell just below 80 percent (Fig. 3). At this lower water content, adhesion-ripple growth stopped and ripple forms began to be eroded by the saltating sand grains (Fig. 4D). With decreasing capillary moisture, adhesion-ripple angle of climb diminished. Hunter (1973) noted that adhesion ripples climb steeply at first but that the angle of climb decreases upward, producing a convex-up curvature of the layering. This change in the angle of climb likely reflects decreasing water content with growth.

Within the lower levels of water content in which adhesion ripples formed, they were less effective sediment traps. Some saltation continued on the damp surface, and coarser grains were seen to jostle along the surface by creep. These adhesion ripples could, therefore, extend farther downwind from their dry sand source than adhesion ripples formed at higher water contents. In addition, adhesion-ripple overhanging ridges became less pronounced (Fig. 4C), primarily because of the filling of voids beneath the ridges by coarser grains in creep as they fell into the voids. By this process, the pseudo-cross-lamination developed alternating coarser and finer laminae—the finer laminae representing the actual adhesion-ripple ridge formed by the adhering of grains in saltation, with the coarser laminae representing the filling of cavities beneath the overhanging ridges by grains in creep (Fig. 6). Occasionally, an overhanging ridge collapsed, forming an isolated pocket of coarser grains. Alternating coarser and finer laminae in climbing-adhesion-ripple structures was a feature we first noticed in the Cambrian Galesville Sandstone, but until doing the experiments we were unable to explain it.

The angle of impact of saltating grains also

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**Fig. 5.**—Epoxy peel showing pseudo-cross-lamination formed experimentally by climbing adhesion ripples shown in Figure 4. Surfaces of discontinuity (arrows) formed by the termination of capillary moisture and cessation of adhesion ripple growth. Wind was from the left.

**Fig. 6.**—Schematic illustration of the formation of alternating coarse and fine laminations in adhesion ripple pseudo-cross-lamination.
affected adhesion-ripple morphology. Reineck (1955) noted that sand blown at different angles on a wet depositional surface produced adhesion ripples of different shapes. A low angle produced wide adhesion ripples of low amplitudes, whereas a high angle produced numerous adhesion ripples of high amplitudes. In our experiments, by “eyeball approximation,” it seemed apparent that upon a level depositional surface under wind velocities in the range for saltation to occur, adhesion ripples, hence also their pseudo-cross-lamination, climb upwind from the depositional surface at the angle of impact for saltating grains (Fig. 3). In our experiments with a completely flat depositional surface and saltating-grain “runway,” adhesion ripples climbed at about 15 degrees, a figure highly compatible with that Bagnold (1941) found for the impact angle of saltating grains (10–16 degrees).

Clearly, in nature deviations from this ideal impact angle are common. In the experience of the senior author with natural adhesion ripples on Padre Island, south Texas, many adhesion ripples climb at the ideal impact angle, but a much wider spectrum of climb angles occurs. Local inclination of the depositional surface to the surface upon which the sand-supplying saltating grains are moving, other small topographic irregularities such as microtopography, variation in wind velocity, and water content are common causes for departure from the ideal impact angle.

As noted above, in our experiments local tilting of the depositional surface and, hence, change in the grain impact angle produced marked changes in the angle of climb. Adhesion ripples forming on a depositional surface dipping into the wind climbed at a much steeper angle than those forming on a level surface (Fig. 3). In contrast, depositional surfaces dipping downwind produced small angles of climb, with adhesion-ripple relief being nil and sheets of adhered grains occurring at about 13 degrees, the angle at which the depositional surface and the impacting grain trajectories were about parallel (Fig. 3). Similarly, introducing grains from higher or lower angles than those of normally impacting saltating grains produced adhesion ripples climbing at steep or very low angles, respectively (Fig. 3). These inclinations of the depositional surface that we performed in the wind tunnel simulate very local irregularities in nature. On a broad sloping depositional surface, streamlines would adjust to be parallel to it and adhesion ripples would climb at angle more approaching the ideal (measured with respect to the depositional surface).

In the same sense, changes in wind velocity produced different adhesion-ripple angles of climb. Grain paths tend to approach the horizontal at high wind velocities (upper-flow-regime bed), and the angle of climb of adhesion ripples decreases accordingly. We feel this is less important in producing low angles of adhesion-ripple climb than local sloping of the depositional surfaces because such high wind velocities are generally less frequent than those velocities resulting in more typical higher impact angles. Also, unless the depositional surface is extremely wet, the high shear stress of upper flow regime would probably reduce the sand-trapping capabilities of the adhesion ripples and result in very low sedimentation rates or even net deflation.

Adhesion Warts

Reineck (1955) grew adhesion warts experimentally in strong winds of varying directions. We were unable to duplicate his results experimentally under these same conditions. Using a wind direction spread of up to 180 degrees and sustaining a particular direction for a few moments, adhesion ripples formed on surfaces with a high water content. When the wind direction changed, these adhesion ripples very quickly realigned themselves to the new direction, with momentarily a set of interfering adhesion ripple trends occurring. Cross sections and epoxy peels taken in different orientations showed truncating small sets of adhesion-ripple pseudo-cross-lamination at different orientations (Fig. 3). The open-arched, dome-shaped features evident from Reineck’s experiments were not present. At lower water-saturation levels, irregular adhesion lamination formed with shifting winds (Fig. 3).

Although we have included in Figure 3 shifting wind directions as a possible mechanism to form adhesion warts, we question whether, in nature, this occurs very commonly. Accretion can occur only in one direction at a time—the wind-ward side. For a dome to form, the wind would have to essentially span the compass within very short pe-
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Periods. In addition, given the rapidness with which adhesion ripples can form, we believe that they will form instead of adhesion warts in most natural winds. In the senior author’s experience on Padre Island, wart-appearing structures are either rain-impact features or erosional forms that consist of wind-sculptured adhesion ripples or other features. In cross-section, adhesion-wart structure is not present.

Experimentally, we did produce true adhesion warts by vertical grainfall onto a damp irregular surface. Accreted rims of grains on damp positive surface features formed adhesion-wart structures. In nature, this is probably the most common occurrence of adhesion warts, with the initial small surface projections being very small clumps of organic debris, algal mats, microtopography, or rain-impact features (Fig. 3).

Adhesion Laminations

The formation of adhesion plane bed seems dependent upon water content and the angle formed between grain impact paths and the depositional surface. On level depositional surfaces with water content levels below that favorable for adhesion-ripple development, adhesion plane bed forms (Fig. 3). In our experiments, the accretion of adhesion laminations was a very inefficient process compared to the sand trapping ability of adhesion ripples. Saltation and creep occurred over the depositional surface, and for each grain trapped by adhesion, several grains were seen to go by. Adhesion plane bed, therefore, seemingly could form over a much wider depositional area than adhesion ripples.

The relationship between degree of wetness and formation of adhesion plane bed has been noted previously. Hunter (1980b) stated that adhesion plane bed forms on surfaces with insufficient wetness for adhesion ripples. He illustrated a sequence (Fig. 2, p. 265) showing that, with decreasing wetness, adhesion ripples yield to adhesion plane bed and these, in turn, to wind ripples that form on a dry surface. Similarly, Kocurek (1981) documented a drying-upward sequence in interdune deposits on Padre Island that consists of, from bottom to top, water-lain deposits, climbing-adhesion-ripple structures, adhesion laminations, and wind-ripple deposits. Thus, in nature, a sequence of adhesion-ripple structures, overlain by adhesion laminations, commonly indicates a drying-upward sequence (Fig. 2). It seems to the senior author that on Padre Island, adhesion laminations form their greatest accumulation in gusty winds. A brief gust of wind blows dry sand onto the damp surface; slackening of the wind below threshold velocity for a few moments allows time for these grains to become damp and adhere to the surface.

We found experimentally that adhesion laminations could also be formed by lowering the relative angle between saltating grain paths and the depositional surface, regardless of water content. Either tilting the depositional surface at low angles downwind or introducing grains at very low angles resulted in the grain-impact angle being essentially parallel to the depositional surface, and adhesion plane bed occurred (Fig. 3). In nature, this would simulate a local tilting of the depositional surface. As discussed with adhesion ripples, streamlines would probably become parallel to a widespread sloping depositional surface and saltating grains would assume their typical low-angle impact trajectories measured with respect to the depositional surface. High wind velocities, in which grain paths also become nearly horizontal, produced adhesion laminations (Fig. 3). This mechanism, however, probably accounts for very little adhesion lamina
tion in nature. Winds near or at upper flow regime may produce too great a shear stress for much adhesion to occur.

ANCIENT EXAMPLES

Galesville Sandstone

The Upper Cambrian Galesville Sandstone is one of several enigmatic Lower Paleozoic sandstone blankets on the North American craton. The typically bimodal, fine- to coarse-grained Galesville Sandstone crops out in many places in the upper midwestern United States and has previously been interpreted as a nearshore subaqueous deposit. Locally in the Dells area of south-central Wisconsin, the Galesville has been reinterpreted as a coastal eolian dune erg (Fielder, 1982). Part of this reinterpretation is based upon the recognition of adhesion structures, which, as noted in the introduction of this paper, are abundant. Adhesion structures in the Galesville were first identified by R. E. Hunter during a recent field trip; we, as had all previous workers, had mis-
identified the climbing-adhesion-ripple structures as small-scale tabular cross-strata. Their crinkly appearance was simply attributed to vagaries of cementation and weathering.

Sets of climbing-adhesion-ripple structures, composing up to 40 percent of the thickness of some Galesville outcrops, range from 0.5 cm to 20 cm thick, with an average thickness of about 8 cm (Figs. 7 and 8). They commonly occur in lensoid beds averaging about 4.5 m in length. Laterally, these structures are erosionally truncated or terminate against eolian dune cross-strata. More rarely, climbing-adhesion-ripple structures occur along reactivation surfaces of eolian dunes, or interfinger with dune stratification. In some outcrops, both the plan-view adhesion ripple form is visible on bedding planes, and the corresponding pseudo-cross-lamination is present on cross sections of beds (Fig. 9).

Most examples of Galesville adhesion-ripple pseudo-cross-lamination display alternating coarse and fine laminae. In experiments, as discussed above, this was shown to result from grains in saltation forming the adhesion-ripple ridge, and coarser grains in creep filling cavities beneath overhanging ridges. Alternating laminae of coarse and fine sand greatly enhance the visibility of the climbing-adhesion-ripple structures in outcrop by promoting differential cementation and subsequent prefer-
Adhesion laminations account for up to 10 percent of some intervals in the Galesville. These zones typically overlie climbing-adhesion-ripple structures. No adhesion-wart structures were found.

Recognition of adhesion structures has allowed the establishing of repetitive vertical sequences that compose significant parts of the Galesville (Fig. 10). Both drying-upward and, less commonly, wetting-upward sequences occur. A complete, idealized drying-upward sequence consists of, from bottom to top, festoon cross-strata interpreted as shoreface deposits, low-angle cross-strata thought to be beach laminations, well-formed climbing-adhesion-ripple structures, poorly formed climbing-adhesion-ripple structures, adhesion laminations, and eolian dune cross-strata. An idealized wetting-upward sequence consists of these same structures in an inverted order. Isolated channels occur that truncate adhesion structures, and these are thought to be run-off channels, draining either tides or precipitation.

The lensoid geometry and lateral interfingerings of adhesion strata with the lower portions of eolian dune stratification suggest that the adhesion ripples formed in wet, low, interdune areas. Galesville climbing-adhesion-ripple structures typically climb at about 14 degrees, an angle of climb produced experimentally by adhesion ripples forming at high water contents, on horizontal depositional surfaces at lower flow regime velocities. The presence of adhesion structures and the vertical and lateral relationships indicate that dry eolian dunes, submerged (probably marine) areas, and wet flats coexisted in the Galesville. Repetitive vertical sequences in the Galesville could have resulted from minor shoreline oscillations or, more simply, lateral migration of dune, interdune, and beach environments with time.

Galesville climbing-adhesion-ripple structures generally lack disconformities, indicating that they reflect single depositional events. Such great thickness of sets of climbing-adhesion-ripple structures as are seen in the Galesville seem unlikely to have occurred with a constant water table. These thicknesses seem more likely to have occurred if the water table was rising, such as would occur when a rising tide gradually floods low interdune areas, or when rain or run-off flow into low areas where water level rises as the pool becomes filled by sediment. Supporting this hypothesis is the presence of alternating coarser and finer laminations throughout entire sets of climbing-adhesion-ripple structures. As noted earlier, experimental observations show that this alter-
nation of laminations forms only in the lower ranges of water saturation level suitable for adhesion-ripple formation. Such a constant water content would be unlikely to be maintained if the adhesion-ripple depositional surface was simply emerging from a pool of water, or was wetted in a single episode, such as a heavy rain. This constant water-content level could be maintained, however, if the rising water table and the dry sand supply were in balance.

Because climbing-adhesion-ripple structures are produced by adhesion-ripple ridges accreting into the wind, they reflect wind directions during deposition and can be used as paleowind indicators. Study of adhesion ripple pseudo-cross-lamination orientation in the Galesville indicates that they are in general agreement with eolian dune cross-strata orientations but show greater scatter. This greater scatter may reflect more complex wind patterns in the low interdune areas or may indicate an additional wind-directional component such as storm winds when dunes were wetted and less active.

ST. PETER SANDSTONE

Numerous sets of climbing-adhesion-ripple structures have also been found in one locality of the Ordovician St. Peter Sandstone of Wisconsin. Preliminary survey of several nearby St. Peter outcrops, however, yielded no additional adhesion structures. The St. Peter remains one of the most famous, yet least understood, formations and has been considered both largely eolian and largely marine in origin. The presence of adhesion structures indicates that parts of the St. Peter were deposited subaerially and that both a dry sand source and a wet deposition area existed together.

CONCLUSIONS

Adhesion structures are distinct, important sedimentary structures whose role in the interpretation of ancient deposits has yet to be fully utilized. Their presence in the rock record indicates that both a dry-sand source and a wet or damp depositional area existed simultaneously. Wind tunnel experiments confirm that the different types of adhesion structures reflect specific depositional conditions. Adhesion ripples form only on surfaces with a high water content and are excellent sand traps. With unidirectional winds, individual adhesion ripples climb upwind over each other, producing a set of pseudo-cross-lamination with “foreset” dipping downwind. These form reliable indicators of paleowind directions. Even with shifting wind directions, adhesion ripples can occur by rapidly realigning themselves to the new wind direction, resulting in the deposition of diversely oriented sets of pseudo-cross-lamination. The angle of adhesion-ripple climb is a function of water content, wind velocity, and local angle between saltating grain paths and the depositional surface.

Adhesion plane bed can form as a continuation of the adhesion process, where water content falls below a critical level and sand adhesion occurs by the inefficient process of grains adhering in thin sheets. Adhesion plane bed can also form at any water content if the angle between saltating grain paths and the depositional surface is either nearly zero or perpendicular. An upward sequence of climbing-adhesion-ripple structures to adhesion laminations can be taken as either a drying-upward sequence or, probably far less commonly, a decreasing in wind speed to upper flow regime.

True adhesion warts, in our experience, are the rarest of the adhesion structures and form by means of rainfall onto a surface marked by small irregularities or, more rarely, by means of rapidly shifting winds. Many surfaces that appear to contain adhesion warts are erosional and lack the internal structure of adhesion warts.

We consider evaporite-adhesion structures to constitute a distinct class separate from the other adhesion structures because of their morphology and origin.

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