

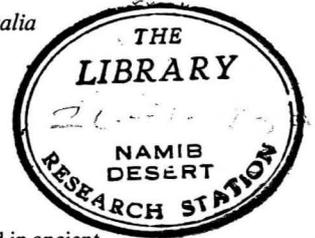
For Mary Seely wife
our best wishes - and
thanks!
Steve

Aeolian granule ripple deposits, Namibia

STEVEN G. FRYBERGER*, PATRICK HESP† and KATHLEEN HASTINGS†

*Desert Engineering, 2750 Howell Road, Golden, CO 80401, USA

† The Rottneest Island Authority, Post Office, Rottneest Island 6161, Western Australia



ABSTRACT

Granule ripples are a common feature of most dunefields, yet they have seldom been recognized in ancient deposits. Although granule ripples are common in erosional settings, such as windward slopes of dunes, or scour surfaces in interdunes, they nevertheless migrate laterally and leave distinctive deposits that can be recognized in ancient rocks. These deposits have characteristics of 'type B' sand sheet deposits, including: 'poured-in' texture; curving ripple trough; tangential, coarse-grained foresets; irregular silty layers; well-sorted coarse and fine layers (either horizontal or within foresets); and fine layers in ripple troughs. Wind tunnel experiments suggest that under low-velocity wind conditions, granule ripples grow to a significant degree as parasites dependent on saltation of fine sand grains whose impact moves the larger grains of the granule ripple. Although the depositional surface of granule ripples is commonly coated with a layer of coarse grains, this is in most places only a few grains thick. Underlying deposits commonly have a poorly sorted, or 'poured-in' texture. This texture results from an admixture of fine grains that fall among the spaces between the larger grains during deposition.

INTRODUCTION

This report results from field-work conducted near Swakopmund, Namibia, which is located on the coast of the South Atlantic Ocean about 700 km north of the Orange River (Figs 1 & 2). Prior to the senior author's visit, Hesp and Hastings had established a number of photographic and survey sites near Swakopmund and Walvis Bay. The purpose of these sites was to record the response of barchan and dome dunes to the predominantly bimodal wind regime of the area (Hastings and Hesp, in preparation). In support of these studies a number of trenches were dug in the small dunes and associated deposits just south of the Swakop River near Swakopmund (Fig. 2, arrow 1). This site is at the northern terminus of a small sand sea that extends from Walvis Bay to Swakopmund. To the south lies the main Namib Sand Sea, which has its northern terminus along the Kuiseb River (Fig. 2, arrow 3). Some coastal dunes have moved north across the Kuiseb River delta in the area between Walvis Bay and the point of arrow 2 in Fig. 2, which marks the study site on the Kuiseb River delta.

Trenches were located in interdune areas at the

Swakopmund site. Many of these interdunes were partially covered by fields of granule ripples (Fig. 3). The trenches in some places exposed deposits up to 0.3 m thick with sedimentary features comparable to those of granule ripples on the surface. It was concluded that the deposits in question were from granule ripples. The senior author followed the field-work with experiments using a wind sedimentation tunnel. These experiments duplicated under controlled conditions many of the granule ripple features seen in the field. The purpose of this report is to describe the granule ripple deposits, and other deposits that lie above a major unconformity on Precambrian metamorphic rocks and below modern draa deposits.

GEOLOGICAL SETTING

The study area is located in an extremely dry region, with precipitation averaging less than 100 mm per year. A significant portion of this is in the form of fog (McKee, 1982; Ward & Von Brunn, 1985; Ward & Seely, 1989). The geological setting and dunefields of the main Namib Sand Sea have been described in

84101

10178

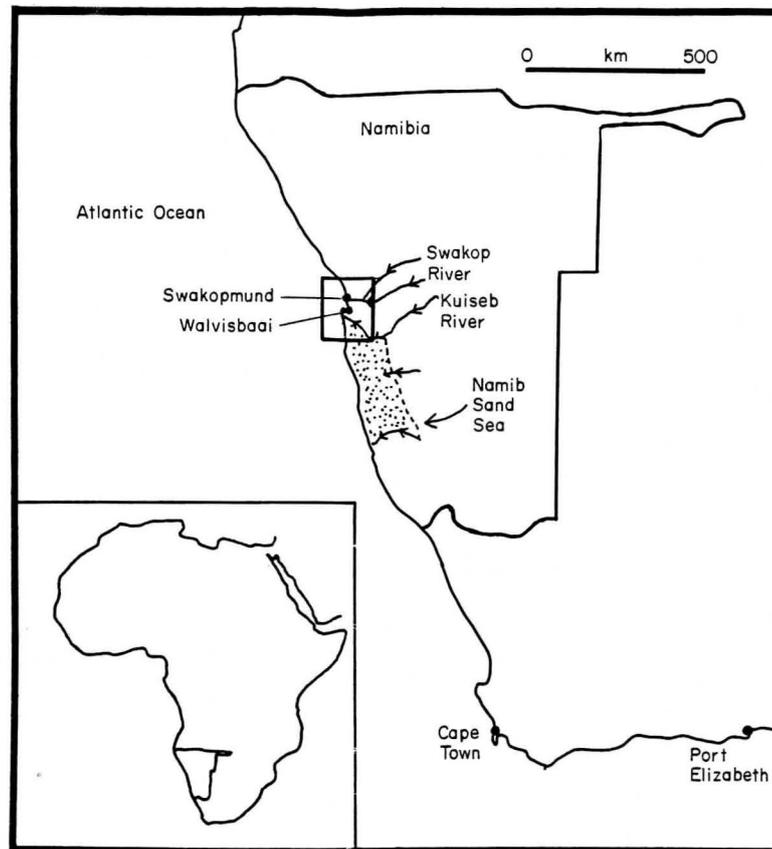


Fig. 1. Location of the study area (outlined, see Fig. 2).

numerous works (e.g. McKee, 1982; Teller & Lancaster, 1985; Ward, 1987; Lancaster, 1988; Lancaster & Teller, 1988; and others referenced therein). The aeolian sediments at site 1 (Fig. 2, arrow 1) constitute a layer 1–5 m thick that overlies the Dammar System Granites which are 1000–570 Ma in age. The erosional surface on these granites is of Cretaceous age and is referred to as the Namib Unconformity (Ward, 1987). Outside the study sites at Swakopmund are a succession of Cenozoic deposits, including the Palaeocene Tsondab Sandstone, Karpenkliff Conglomerate and Kamberge Calcrete (Neogene) and the various silts, conglomerates, carbonates and dune sands of the Namib Desert to the south (Pleistocene–Recent; Ward, 1987).

The wind regime in the study area consists of dominant south-west winds that are stronger in summer, and north-east to east (Berg) winds in winter (Fryberger, 1979; Ward & Von Brunn, 1985; Lancas-

ter, 1985, 1988; open arrows in Fig. 2). Lancaster (1985) states that the SSE–SSW sector (40–50% of all winds) is the dominant sand flow sector near the coast, representing 80–90% of sand drift at a meteorological station on the Kuiseb River delta (see figs 2 & 5 in Lancaster, 1985). However, some 40 km inland at Rooibank, east to north-east winds are dominant and account for 60–65% of annual sand drift. Our sites, on the north-east margin of the Walvis Bay–Swakopmund sand sea may be influenced more by easterly winds than Lancaster's Kuiseb River station further south (Hastings and Hesp, in preparation). Whatever the precise balance may be, both wind regimes at our Swakopmund site are capable of causing substantial sand movement. These data, plus cross-bedding dip directions within the granule ripples, confirm that they have formed in a bimodal effective wind regime.

Our studies were conducted in winter. A strong Berg wind gusting at up to 18 m s^{-1} occurred 24 days

8F101

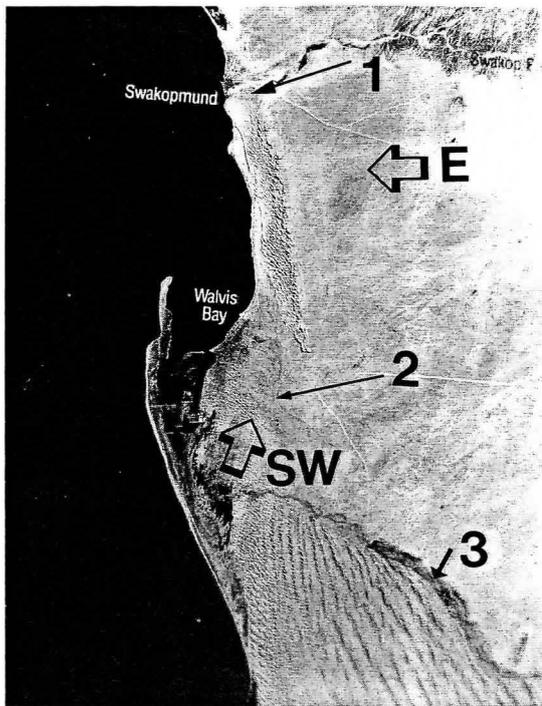


Fig. 2. Landsat image of the study areas near Swakopmund (arrow 1) and Walvis Bay (arrow 2). Open arrows show principal wind directions. Arrow 3 shows the Kuiseb River. The Swakop River runs just north of arrow 1.

previously. The storm lasted for 3 days, causing rapid sand transport. A relatively strong south-west wind that produced a day of sand transport occurred 7 days before our study took place. During our study, however, only gentle south-west winds were experienced, with little sand movement. This was one of the main reasons for the wind tunnel study. Using the wind tunnel, granule ripple deposition could be observed under controlled conditions as a check on inferences based on inactive ripples seen in the field.

The sediments of the study area near Swakopmund consist of both aeolian sands and silty, muddy, micaceous, fluvial overbank deposits. The aeolian deposits consist of two populations. The first is reddish, fine-grained (median of 0.2 mm), well-sorted dune sand derived predominantly from the coast and the main Namib Sand Sea to the south. These fine-grained sands contain up to 50% garnet and biotite that causes the crestal areas of some dunes to appear dark (Fig. 3A, D). A second group of sands consists of coarse grains and granules weathered largely from

underlying Precambrian rocks including white marbles and quartz veins, which partially accounts for the light colour of the granule ripples (Fig. 3C).

The main study site is just south of the Swakop River channel above a terrace cut by the river. In interdunes of this area, relict, wind-scoured fluvial silts and muds deposited by the Swakop River are widespread (white arrow, Fig. 3C). Small barchan and dome dunes are the main bedform type at this site (Fig. 3). To the south are the large draa deposits that are slowly advancing northward (Fig. 3A, C). Occasional flooding of the Swakop River has effectively stopped northward migration of the dunefield, although some dunes had entered the modern channel at the time of our study. Our trenches were dug at sites such as those shown in Fig. 3(B), generally low areas with abundant poorly sorted sand.

GRANULE RIPPLE DEPOSITS

Large granule ripples

Large granule ripples are common throughout the study area and resemble those described by other workers (e.g. Bagnold, 1941; Sharp, 1963; Ellwood *et al.*, 1975; Figs 5 & 6). Most have cross-bedding that indicates lateral migration. For example, the granule ripple crest in Fig. 5(B) has clearly shifted from left to right. The crestal position is marked by coarse layers that were buried and preserved by fines, probably due to changes in effective wind direction and strength. Likewise, foresets within the granule ripple described by Sharp (1963; Fig. 6C) indicate that it moved laterally during development. There were other large granule ripples in the study area that bore a record of considerable lateral growth or movement (Fig. 7). Lateral shift of the crest of the large granule ripple shown in Fig. 7(A) has produced a broad, flat morphology reminiscent of an alluvial bar.

Sites at both Walvis Bay and Swakopmund were monitored over 6 months by Hesp and Hastings, using photogrammetric techniques. These data revealed that all granule ripples occasionally reverse their asymmetric form and migrate downwind under the strongest storm winds. As would be expected smaller granule ripples were proportionately more responsive to storm winds than large ones.

The composite erosional and depositional origins of some large granule ripples is evident in our trenches. For example, the trench in Fig. 5(A) shows that the upper portion of the ripple consists of foreset bedding

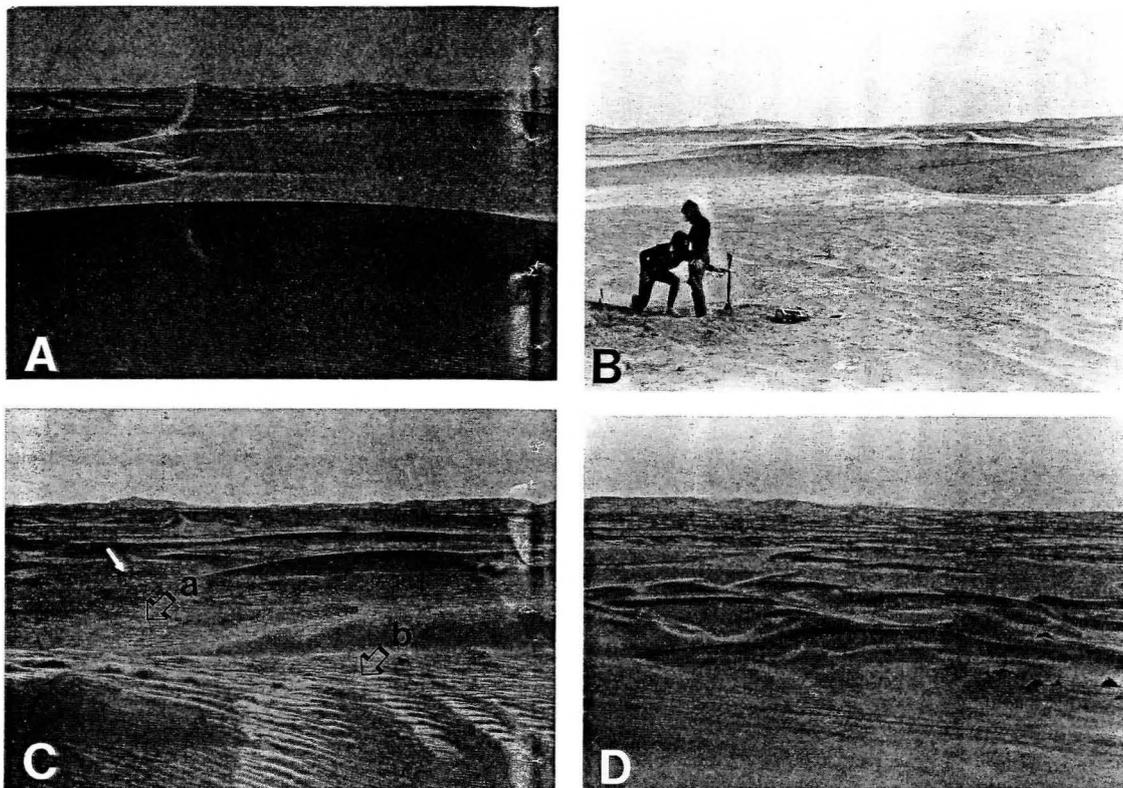


Fig. 3. Views of the northern study area, just south of the Swakop River. (A) View looking south of interdune coarse sands and gravels with a large draa in the distance. (B) Typical study site showing granule ripples in the foreground and dunes advancing from the middle distance. (C) Another part of the study area showing interdune granule ripples (arrow a) and granule ripples on the windward slope of a barchan (arrow b). White arrow shows wind-scoured silty fluvial deposits. (D) View looking south, with many small barchan dunes; the crests are darkened by concentrations of biotite and garnet.

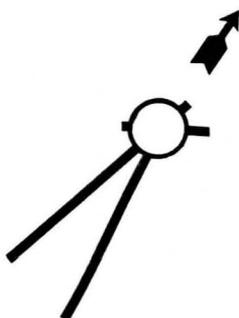


Fig. 4. Sand rose, based on surface wind records for Walvis Bay, showing principal directions from which sand is likely to be transported. Arms are proportional in length to potential sand movement (drift potential). From Breed *et al.* (1979).

resulting from ripple growth. On the other hand, the lower slopes of the ripple form are cut into dune bedding. Thus, the morphology of some granule ripples can reflect both constructional and scour processes.

Although granule ripples and their deposits are mainly constructional features, they are commonly found in erosional settings such as interdunes, or the windward slopes of dunes. Perhaps removal of fine sand in such settings concentrates the coarse grains required to build granule ripples. Once a sufficient concentration of coarse grains is reached, granule ripples may begin to grow, despite the fact that fine sand is being scoured around them.

The concentration of coarse grains and granules at the crest and the layer of coarse grains on the slopes of the ripples are the main identifying features of all



Fig. 5. Large granule ripples. (A) Partly erosional, partly depositional in nature, this ripple has the typical coarse grains on the crest (white arrow). Note that the ripple form truncates underlying subhorizontal strata. (B) Large granule ripple that has moved slightly, depositing thin coarse layers (arrows 1 and 2) between thick fine layers while building from left to right.

granule ripples. The relatively large ripple forms and their deposits can be preserved if they are buried by a dune, even in a relatively high topographic position (see Fig. 12). Another feature typical of these granule ripple deposits is alternation of coarse and fine sand layers in the ripple foresets. Coarse layers commonly thicken where traced upward toward the crest of the bedform.

Small granule ripples

The smaller bedforms (<50 cm in width) were common in the study area, and had formed deposits up to 30 cm thick (Fig. 8). Features typical of granule ripples at the surface were commonly exposed in the

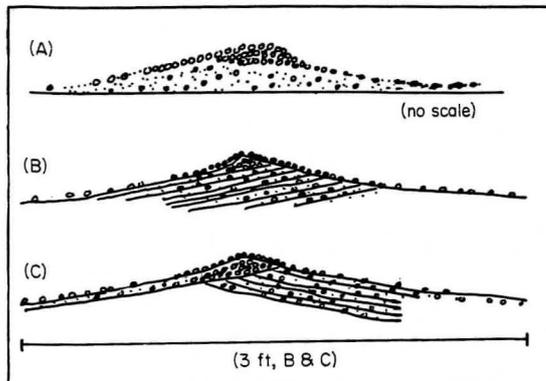


Fig. 6. Bagnold's (1941) and Sharp's (1963) descriptions of granule ripples. (A) Bagnold's granule ripple created in a wind tunnel. The 'poured-in' texture typical of that seen in Namibia and produced in our wind tunnel is reflected in this drawing. (B, C) Sharp's sketches of granule ripples showing a surface layer of coarse grains, with fine sand inside ripples, and cross-strata suggesting lateral migration of the ripples.

trenches. For example, we frequently saw a poorly sorted, unlayered or chaotic arrangement of fine and coarse grains in these deposits referred to informally as 'poured-in' texture (Fig. 8). This is shown by arrows 1 in Fig. 8(A) and matched by similar layers (arrows 2) in the preserved deposits. The source of fine layers is the fine sand collected in the ripple troughs at the surface, and that falling between large grains during sandstorms (Fig. 8B, arrow; see also fine laminations arrow 2 in Fig. 8C). The slight curvature formed by troughs between ripples is apparently sometimes preserved (Fig. 8C, arrow 3).

In some places, well-sorted ripples are preserved in their entirety, as if frozen within surrounding sediments having the typical 'poured-in' texture (Fig. 8D). Note that the poor overall sorting of the deposits in the trenches would not be immediately predicted from the appearance of surficial deposits in Fig. 8(B). This surprising relationship was duplicated in wind tunnel experiments, described in the following section. Most of the trenches in granule ripple deposits had numerous coarse layers only a few grains thick that rather than being preserved lag deposits (i.e. representing deflation without granule ripples present), are more likely preserved portions of individual ripple foresets, crests and windward slopes (Fig. 9).

We became familiar enough with granule ripple deposits to recognize them in the study area where there were no contiguous surface deposits of similar

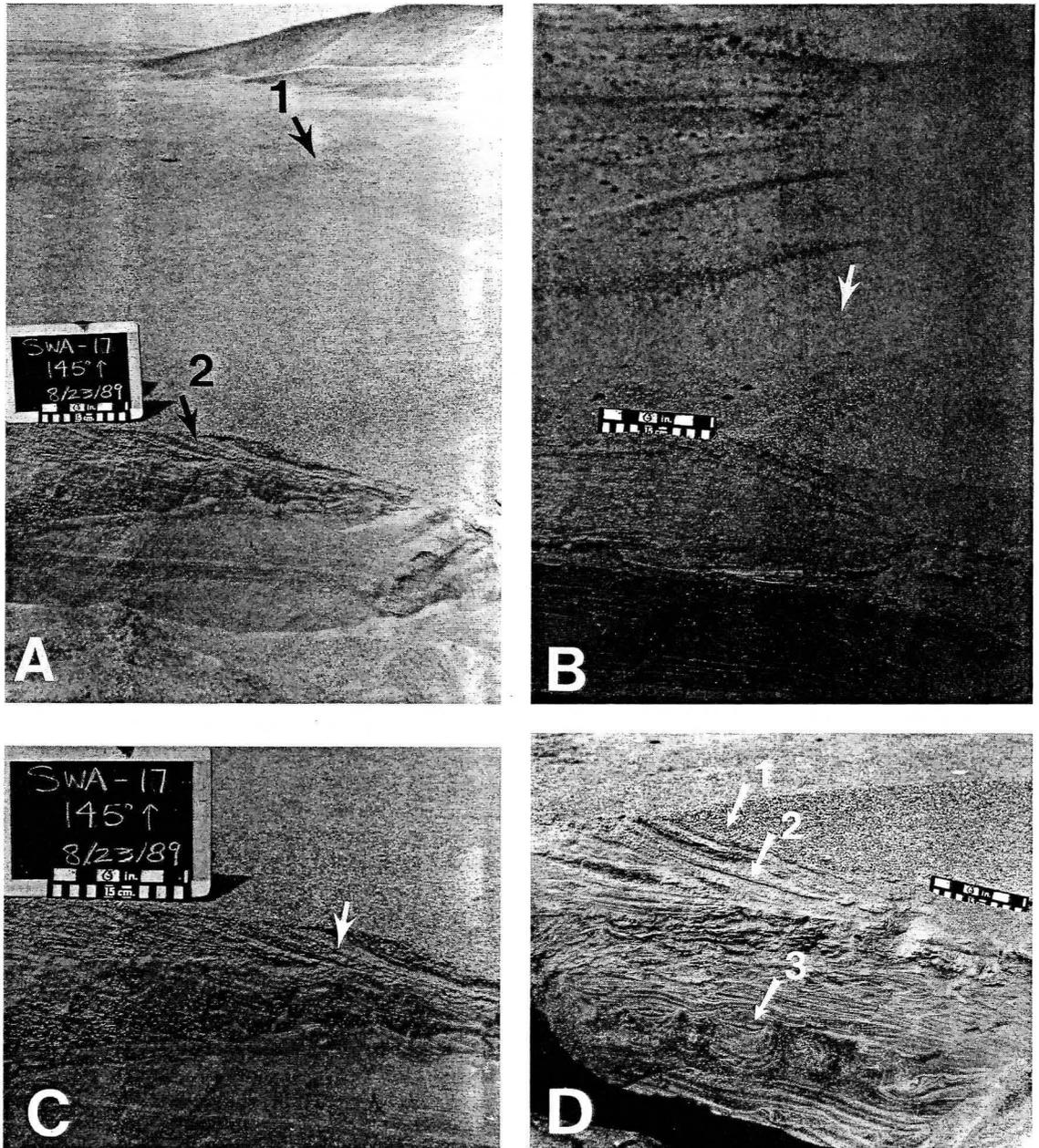


Fig. 7. Large granule ripples. (A) Ripple whose crest is best visible in the distance (arrow 1) has moved from left to right, creating foresets shown by arrow 2. Note tangential foresets formed because the ripple does not have a slipface at the trench site. A 'rollface' would perhaps be a more appropriate description. Note also that the foresets dip to the south-west, indicating that this portion of the ripple has grown in response to the Berg wind. (B) Another view of the ripple shown in Fig. 5(B), with a better view of the fine sand filling hollows between ripples. (C) Close-up of foresets formed by ripple in (A). A light-coloured fine layer is just above the coarse layer at the tip of the white arrow (cf. Fig. 13A, arrow B; and Fig. 13D, arrow A). (D) A granule ripple resting on silty fluvial deposits. Arrow 1 shows coarse grains on the ripple surface, arrow 2 shows a coarse layer within the ripple that thickens toward the surface. Note contorted strata in silty fluvial deposits (arrow 3) similar to those described by Fryberger *et al.* (1990a, b) in tidally flooded sands at Guerrero Negro, Mexico.

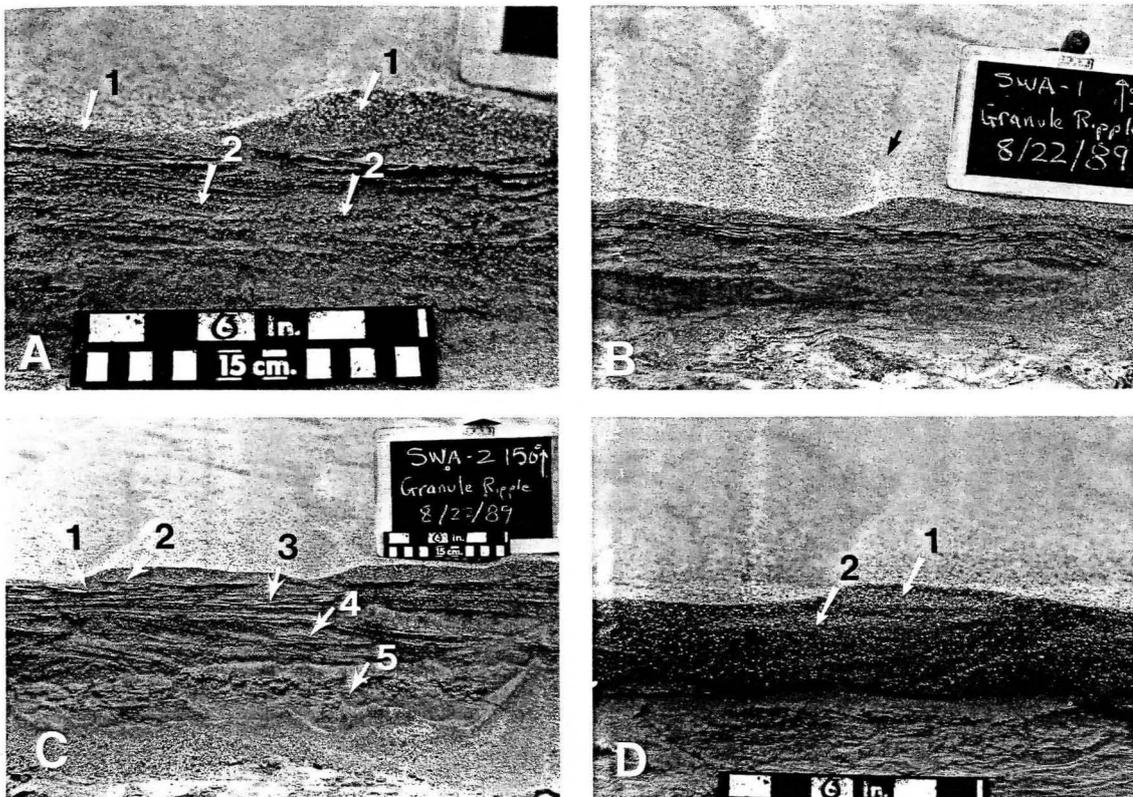


Fig. 8. Small granule ripples: comparison of surface and buried features. (A) 'Poured-in' texture (arrows 1) is visible in underlying deposits. Arrows 2 show coarse layers, gently curving and of uneven thickness, that reflect preserved coarse-grained portions of granule ripples. (B) Fine sand in troughs of granule ripples, with an 'armour' of coarse grains defining the surface of the ripple. Underlying deposits incorporate much fine material. (C) Fine layers at the surface are reflected by fine sand preserved in granule ripple deposits (arrow 2). Curve of ripple trough (arrow 1) is reflected in preserved deposits (arrow 3). Foresets of a larger granule ripple are shown by arrow 4. Silty fluvial deposits are shown by arrow 5. (D) Coarse grains comprising the core of a surface granule ripple (arrow 1) are mirrored in a preserved ripple below (arrow 2).

origin. For example, the lower two-thirds of the trench shown in Fig. 10 consists of the deposits of small and large granule ripples and some antecedent deposits.

WIND TUNNEL EXPERIMENTS

In order to gain a better understanding of granule ripple formation and movement, and the sedimentary features of the resulting deposits, further studies were undertaken in a portable wind tunnel. The sand used in the tunnel was collected from granule ripples at Great Sand Dunes, Colorado. Textural properties were similar to the sands used by Fryberger & Schenk (1981) with more of the coarse sand grains. It was

poorly sorted with light-coloured coarse grains (quartz and feldspar) and dark (magnetite) fine grains. The results of the experiments are summarized in Figs 11 & 12. In one experiment, artificially created bedforms rapidly acquired a surface layer of coarse grains similar to that seen on granule ripples in the Namibia study, mainly due to removal of fine sand downwind. The artificial bedforms then migrated downwind. This occurred as the large grains moved in surface creep caused by saltation impact of fine sand fed into the tunnel at the upwind end (Fig. 11C, E). This fine sand came from the original material, and was collected and recycled from the settling part of the tunnel at the downwind end. However, it was better sorted overall than the sand with which the experi-

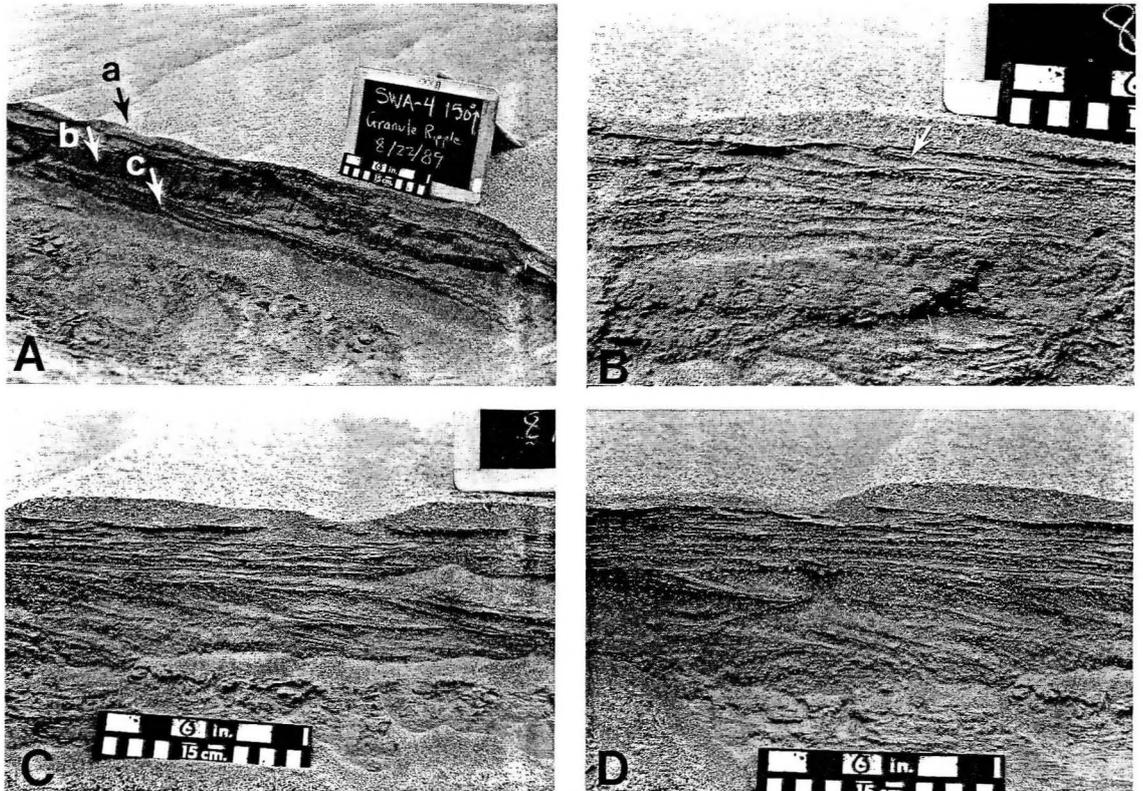


Fig. 9. Details of small granule ripples. (A) Surface consisting mainly of coarse grains (arrow a) overlies several centimetres of granule ripple deposits. Arrow b shows a fine layer of unknown origin. Arrow c shows foresets of larger granule ripples than those at the surface. (B) Granule ripple foresets (arrow) and coarse and fine layers typical of these deposits. (C) Fining-upward sequence in terms of strata, from foresets of large granule ripples at the base, to flat layers at the trench top. Silty fluvial deposits are found at the base of the trench. (D) Detail of cut and fill in granule ripple deposits (left side of trench).

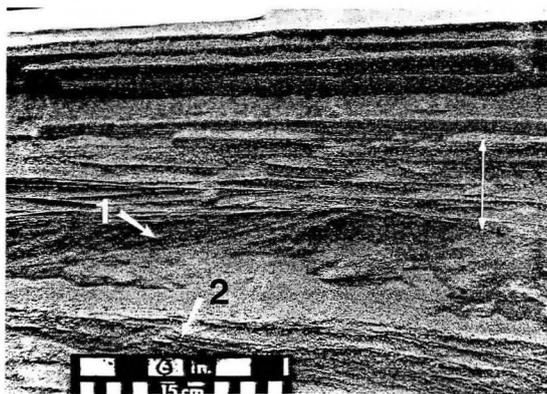


Fig. 10. Interpreted granule ripple deposits in modern sands of the study area. Arrow 1 shows foresets of a large granule ripple (partly erosional of deposits on the right side of the layer). Arrow 2, underlying layer of granule ripple deposits. Double arrow shows a layer of granule ripple deposits, overlain in turn by wind ripple deposits, possibly part of a dune.

ments were begun, because the granule-sized grains were left behind in the newly formed granule ripples, or as a small pile at the base of the sand feed inlet.

Although photographs do not show it well, the deposits of the migrating artificial bedforms had the 'poured-in' texture seen in the study trenches in Namibia. This texture was also produced in a later experiment in which bedforms evolved from a flat surface (Fig. 11A).

As mentioned above, one of the more interesting experiments started with a flat bed (Fig. 11A). A few minutes after the experiment was started, small granule ripples formed and migrated downwind (Fig. 11B, D). Exactly as seen in the Namibia study fine grains collected in the troughs of the granule ripples. The 'poured-in' texture typical of the Namibian granule ripple deposits developed in the wind tunnel where small grains from the saltating population fell into spaces among the larger grains that had

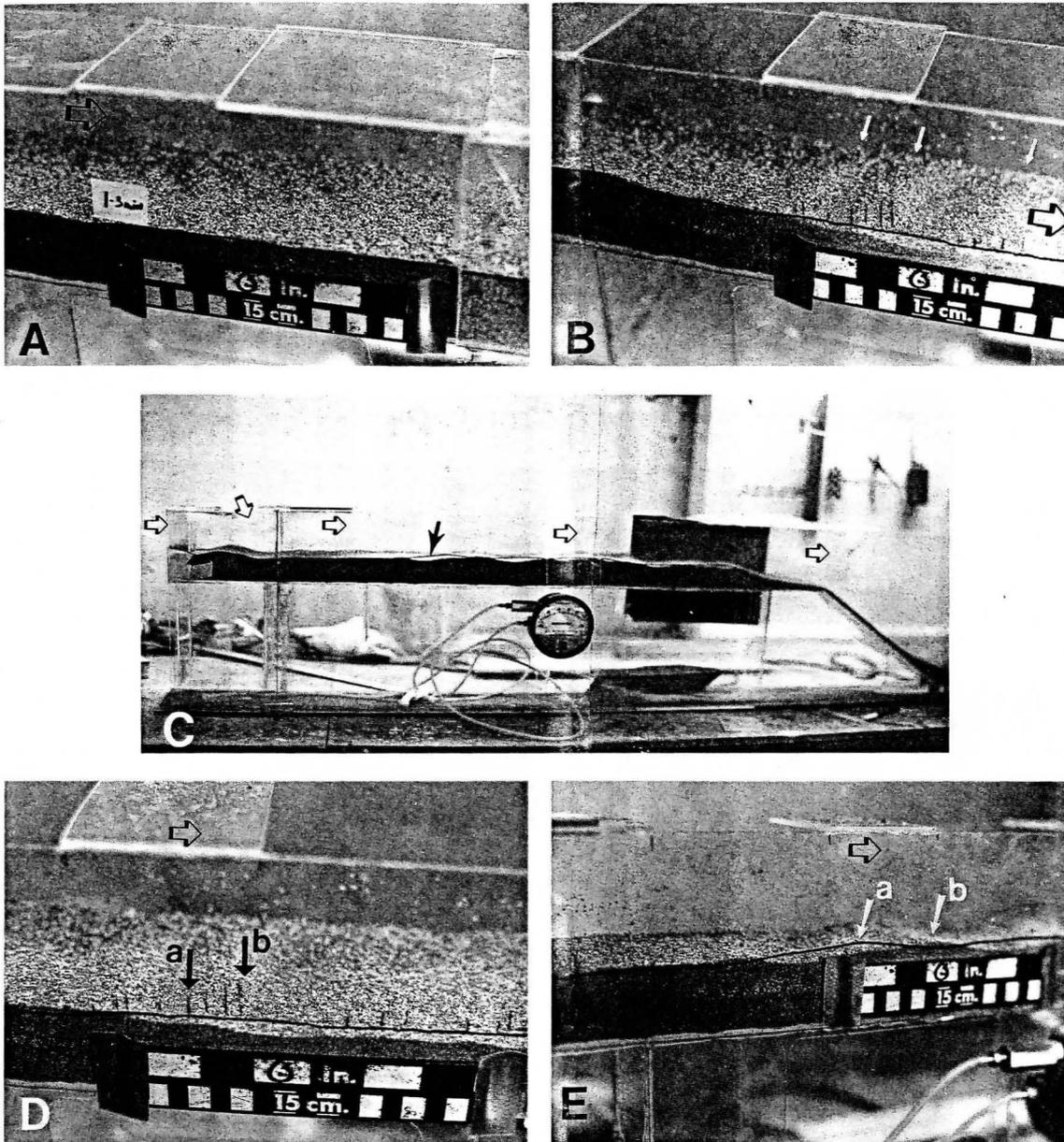


Fig. 11. Wind tunnel experiments. (A) Shortly after the start of an experiment that began with a smooth surface. (B) About 20 min later, granule ripples have formed and moved about 1 cm every 5 min, as reflected by dark vertical marks on tunnel, showing the position of ripple crests through time. (C) Wind tunnel during an experiment with artificial granule ripples shows displacement of bedforms downwind, as well as overall tunnel design. Solid arrow shows the line traced along the crest of an artificial bedform before it moved downwind to the right. Open arrows show the path of wind along tunnel. (D) Close-up of granule ripples formed from a flat surface. Note coarse grains at the surface, with fine sand beginning to collect in troughs exactly as was seen in the modern deposits in Namibia. Arrow a shows the starting position of the crest just after a ripple was formed; arrow b shows its position following migration downwind. (E) Close-up of tunnel showing (by means of marker line on side of tunnel) the movement of the artificial bedform from a to b. In all photographs, wind direction is shown by open arrows.

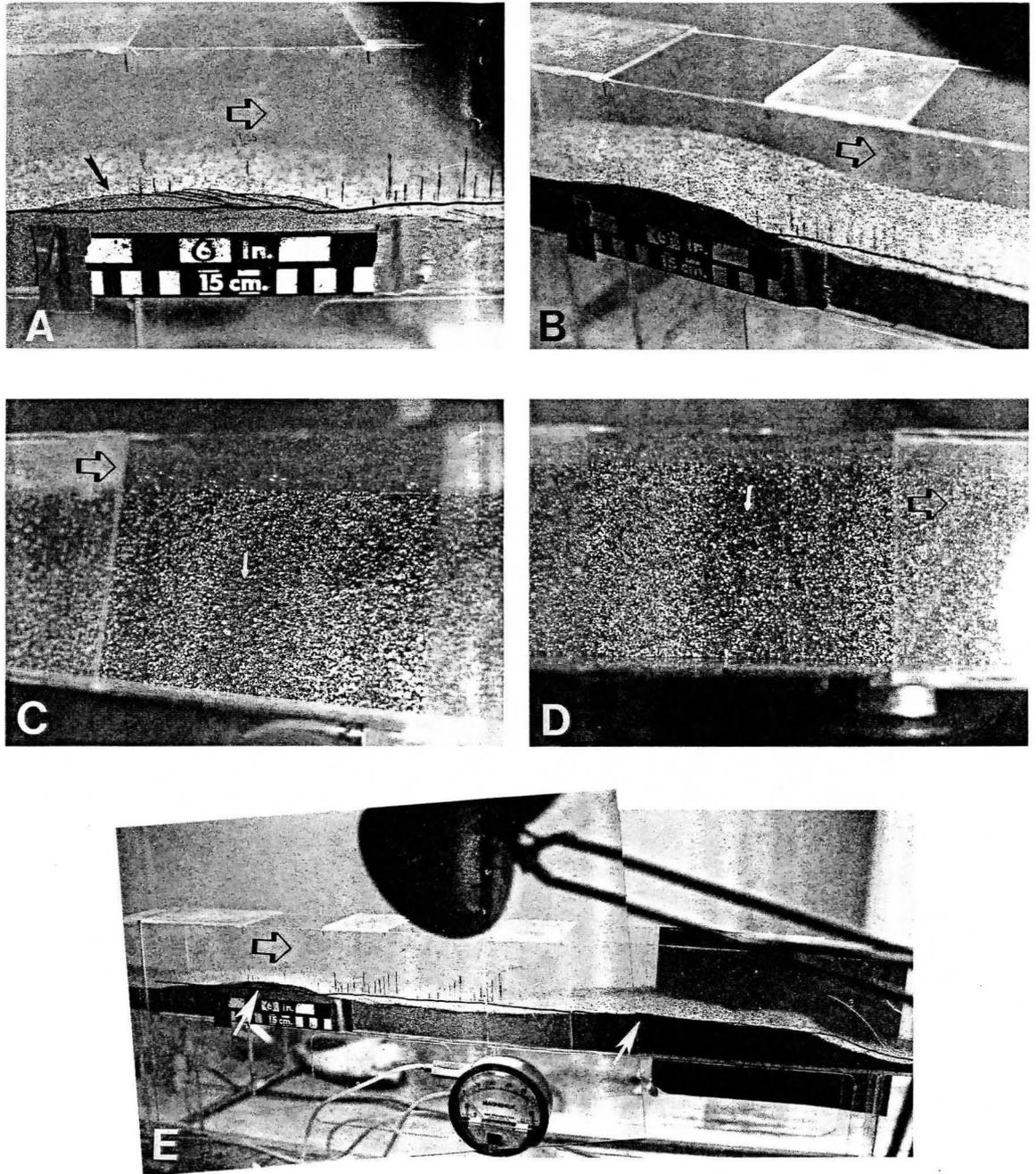


Fig. 12. Wind tunnel experiments. (A) Tracings of successive crest and rollface positions reveal the movement downwind (at approximately 5-min intervals) of a granule ripple formed at the upwind end of the tunnel. Dark, solid arrow shows 'poured-in' texture formed by the ripple despite the uniform surface of coarse grains visible in (B). (C) A plan view of sand surface earlier in the experiment showing dark, fine grains (white arrow) in troughs of light-coloured coarse granule ripples: (D) a later stage of the same experiment; the ripples have grown in size. (E) The final stage of the experiment that began with an originally flat surface, shown by a dark line on the side of the tunnel. White arrows show two granule ripples or 'proto' granule ripples, and scour in the intervening area.

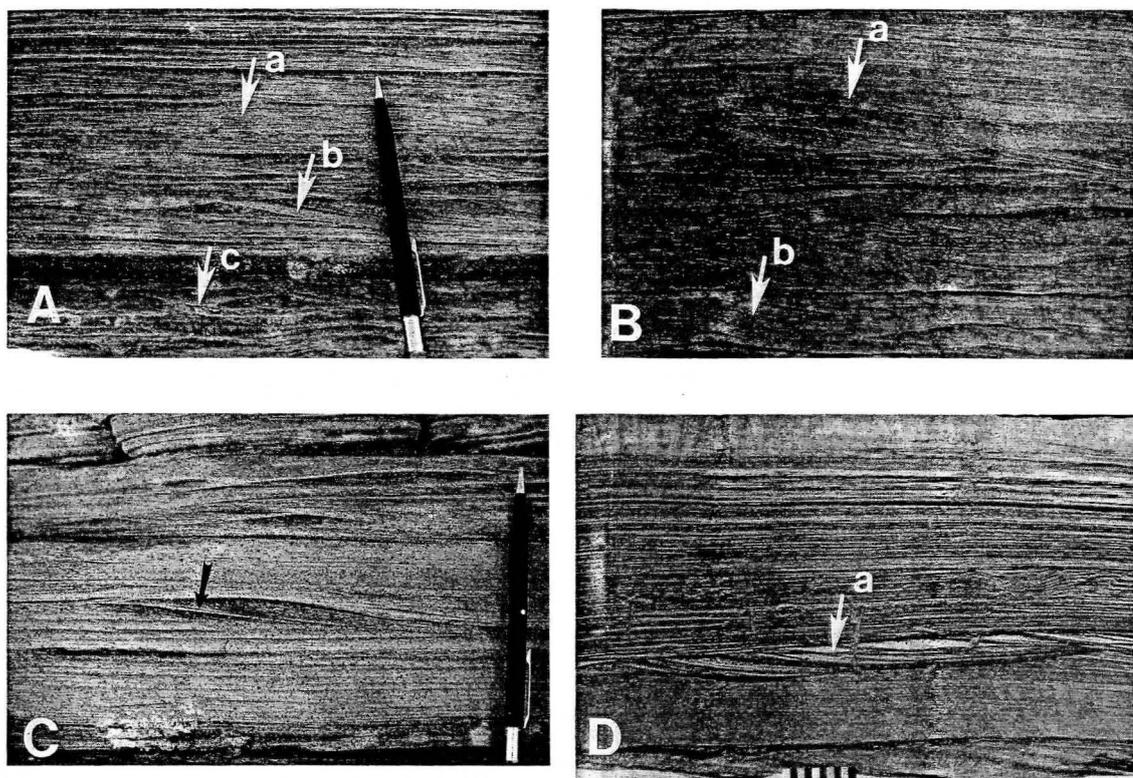


Fig. 13. Ancient and modern examples of granule ripple deposits. (A–C) Ancient granule ripple deposits in the Jurassic Nugget Sandstone, Buckhorn Wash, Utah, identical in many ways to modern deposits in Namibia. (A) Fine and coarse layers form a texture typical of modern deposits (arrow a); fine foreset layer of granule ripple (arrow b); trough of granule ripple (arrow c). (B) Foresets of large granule ripples (arrow a); slight curvature of deposits typical of granule ripples (arrow b). (C) A layer of coarse grains (arrow) formed as a granule ripple built to the right by better sorted sand of wind ripples. (D) Granule ripple deposits (arrow a) in a sand sheet, Eastern Province, Saudi Arabia.

come to rest on the surface. The stationary position, however temporary, of the larger grains was the necessary first step for the fines to be permanently deposited.

During the experiments, saltation rate was controlled by variable sand feed at the upwind end of the tunnel, as well as by wind velocity adjustments. Wind velocity varied from just above threshold, to that which produced rapid saltation of fine- and medium-grained sands. It remained below that which would cause the granules to saltate as a population, although occasionally one or more would be kicked into the airstream by impact of fine- and medium-grained sand. Under these conditions, the movement of the granules resulted mainly from impact by the smaller grains saltating along the tunnel.

At high wind velocity, the fine grains saltated through the tunnel in a steady cloud, causing rapid surface creep of the coarse grains by impact. At lower wind speeds, fine sand remained in the troughs of the granule ripples and surface creep was much slower (Fig. 12C, D). After roughly 3 h of saltation, two large granule ripples or 'proto' granule ripples developed along the length of the tunnel from the original flat surface (Fig. 12E). The large bedform at the mouth of the tunnel grew laterally and vertically, producing a poorly sorted deposit, i.e. the 'poured-in' texture (Fig. 12A). One hour later the bedforms reached a state in which change was very slow. Following this, numerous buckets of sand were blown down the tunnel with little further result except for a slight upward growth and slow downwind migration of the ripples.

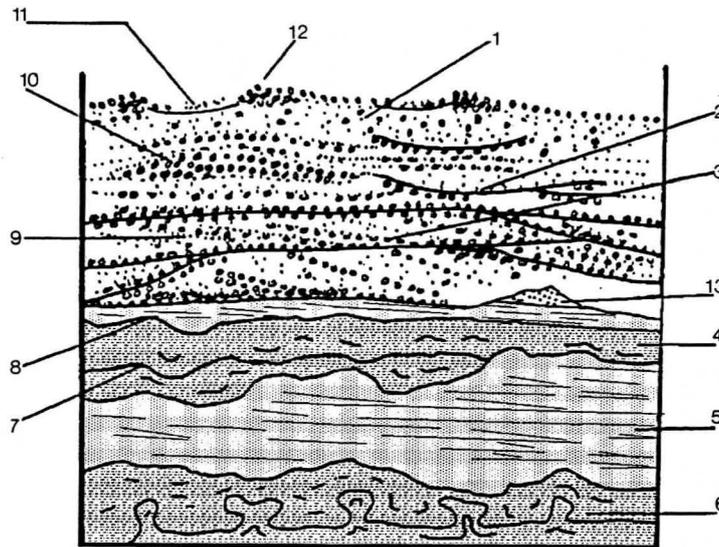


Fig. 14. Summary diagram illustrating distinctive features of granule ripple and associated deposits, Namibia: (1) 'poured-in' texture; (2) curving trough of ripple; (3) tangential, coarse-grained foreset of larger ripple; (4) irregular silty layer (fluvial overbank); (5) well-sorted wind ripple deposits; (6) contorted strata in fluvial silts; (7) erosional surfaces within fluvial silts; (8) coarse layer of granule ripple; (9) well-sorted fine layers of various thicknesses in ripple foresets; (10) ripple form preserved as coarse-grained mound; (11) finer layers in trough of ripple; (12) coarse grains on ripple crest; (13) large granule ripple formed partly by deposition of cross-strata, and partly by erosion of underlying layers.

The ripples produced in these experiments are different from the 'wind ripples' created by Fryberger & Schenk (1981). In these earlier experiments at the US Geological Survey (USGS) the wind ripples were made from better sorted sand, under conditions of net deposition, and granule ripples never formed. In the USGS experiments Fryberger and Schenk were able to make the wind ripples climb at angles from subcritical to supercritical (terminology from Hunter, 1977), by regulating sand feed and wind velocity. In the present experiments, granule ripples formed rapidly, and soon merged into the large mounds in the tunnel. It was not possible to make the bedforms climb, perhaps due to lack of time or the size and the aerodynamic limitations of the tunnel. However, it is apparent from both field and laboratory data presented here that granule ripples and ridges are extremely durable, slow-moving bedforms.

It should be noted that the wind tunnel is small, and does not have the capability for sophisticated experiments. Although the present study duplicated a number of internal and surface features, and processes of granule ripple development, the topic of granule ripple migration should be given further study. In particular, it would be useful to know more about the

roles of saltation and surface creep in granule ripples as a function of wind velocity, particularly at high wind speeds. Moreover, the circumstances that lead to preservation of granule ripple deposits could benefit from further study.

OTHER GRANULE RIPPLE DEPOSITS

The best examples of ancient granule ripple deposits known to us are in outcrops of the Nugget Sandstone at Buckhorn Wash, Utah (Fig. 13A–C). These photographs were previously published with different labelling as examples of sand sheet deposits (fig. 10 in Fryberger *et al.*, 1979). At the time of the previous work, we recognized 'type A' and 'type B' deposits within sand sheets. It is now apparent, as can be confirmed by comparing the modern examples just provided with the ancient ones shown here, that the 'type B' deposits are at least partly granule ripple deposits. The final example of granule ripple deposits is from a modern sand sheet in the Eastern Province of Saudi Arabia, where a lens-shaped layer of granule ripple deposits has been preserved between wind ripple deposits (Fig. 13D).

SUMMARY

This report provides evidence that granule ripples can migrate and leave deposits that can be identified in both modern and ancient sediments. Results of wind tunnel experiments suggest that granule ripples at low wind velocities may to some extent be parasitic forms; the coarse grains that comprise the granule ripple move by surface creep produced as a result of a saltating curtain of finer grains. This depends, however, on wind velocity. At high wind velocity granule- and gravel-sized particles have been known to saltate. Under such conditions it seems possible that granule ripples could form from saltation of granule-sized grains.

In contrast, 'wind' ripples are associated with fine- or medium-grained sand, good sorting, a high percentage of grains in saltation, and a lack of the surface armouring typical of granule ripples. Nevertheless, granule ripples incorporate a significant volume of fine sand in the final deposit as discrete layers, or in zones with a 'poured-in' poorly sorted texture. As noted by other workers, and supported by our observations, granule ripples are slow moving, very durable forms. Their occurrence in a sedimentary layer may indicate the passage of much fine sand through an area. The sedimentary features of granule ripples and associated deposits are summarized in the schematic diagram of Fig. 14.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Mary Seely, Anton McLachlan, the Desert Ecological Research Unit, the CSIR and the Geological Survey of Namibia, for their assistance to the authors, for sponsorship of the senior author's trip to Namibia to attend the 'Dunes '89' symposium, and for provision of a visiting fellowship to P.H. Also, many thanks to John Ward for field trips and discussions about modern and ancient sand dunes of Namibia. We thank Ampol Exploration (USA) for generous support of the senior author's trip to Namibia. We also wish to thank Ralph Hunter and Nick Lancaster for extremely perceptive and helpful reviews.

REFERENCES

- ANON (1982) *The Geology of South West Africa, Namibia*. The Geological Survey, Windhoek, Namibia, 8 pp.
- BAGNOLD, R.A. (1941) *The Physics of Blown Sand and Desert Dunes*. Methuen and Co., London, 265 pp.
- ELLWOOD, J.M., EVANS, P.D. & WILSON, I.G. (1975) Small scale aeolian bedforms. *J. sedim. Petrol.*, **45**, 554-561.
- FRYBERGER, S.G. (1979) Dune forms and wind regime. In: *A Study of Global Sand Seas* (Ed. by E. D. McKee), *Prof. Pap. US geol. Surv.*, **1054**, 137-169.
- FRYBERGER, S.G., AHLBRANDT, T.S. & ANDREWS, S. (1979) Origin, sedimentary features and significance of low-angle eolian sand sheet deposits, Great Sand Dunes National Monument and vicinity, Colorado. *J. sedim. Petrol.*, **49**, 733-746.
- FRYBERGER, S.G., KRISTINIK, L.F. & SCHENK, C.J. (1990a) Tidally-flooded back-barrier dunefield, Guerrero Negro area, Baja California, Mexico. *Sedimentology*, **37**, 23-43.
- FRYBERGER, S.G., KRISTINIK, L.F. & SCHENK, C.J. (1990b) *Modern and Ancient Eolian Deposits: Petroleum Exploration and Production*. Rocky Mountain Section SEPM, Denver, 248 pp.
- FRYBERGER, S.G. & SCHENK, C.J. (1981) Wind sedimentation tunnel experiments on the origins of aeolian strata. *Sedimentology*, **28**, 805-821.
- HUNTER, R.E. (1977) Basic types of stratification in small eolian dunes. *Sedimentology*, **24**, 361-387.
- LANCASTER, N. (1985) Wind and sand movements in the Namib Sand Sea. *Earth Surf. Processes Landforms*, **10**, 607-619.
- LANCASTER, N. (1988) The development of large aeolian bedforms. *Sediment. Geol.*, **55**, 69-89.
- LANCASTER, N. & TELLER, J.T. (1988) Interdune deposits of the Namib Sand Sea. *Sediment. Geol.*, **55**, 9-107.
- MCKEE, E.D. (1982) Sedimentary structures in dunes of the Namib Desert, South West Africa. *Spec. Pap. geol. Soc. Am.*, **188**, 64 pp.
- SHARP, R.P. (1963) Wind ripples. *J. Geol.*, **71**, 617-636.
- TELLER, J.T. & LANCASTER, N. (1985) History of sediments at Khommabes, Central Namib Desert. *Maddoqua*, **14**, 267-278.
- WARD, J.D. (1987) *The Cenozoic Succession in the Kuiseb Valley, Central Namib Desert*. Geological Survey, Department of Economic Affairs, South West Africa/Namibia, Memoir 9, 124 pp.
- WARD, J.D. & SEELY, M.K. (1989) *Geomorphological Aspects of Dunes in the Central Namib Desert: Dunes '89 Excursion 1A Field Guide*. 95 pp.
- WARD, J.D. & VON BRUNN, V. (1985) Sand dynamics along the lower Kuiseb River. In: *Kuiseb Environment: the Development of a Monitoring Baseline* (Ed. by B. J. Huntley), pp. 21-25. Foundation for Research and Development, CSIR, Pretoria.

