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Cross-Bedded Tidal Megaripples From King Sound, Northwestern Australia

by

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ABSTRACT

Migration of megaripples and sand waves in shallow seas and estuaries suggests a possible model for the formation of widespread marine cross-bedding. Most examples have been studied only externally, many of them from echo-sounding; their internal structure is unknown, but cross-bedding has been assumed. Megaripples in King Sound, northwestern Australia, are exposed at low tide and their internal structure has been examined. Many are cross-bedded with steeply dipping foresets; others are internally structureless, probably because of extreme current velocities. Facing of the foresets indicates that they may be developed by either the flood or ebb tide; the latter predominate. The current direction implied by external morphology appears to be a reliable guide to that indicated by the cross-bedding.

INTRODUCTION

A study of cross-bedding of marine sandstones of the Precambrian Kimberley Basin succession of northwestern Australia, involving the systematic measurement of more than 3,500 cross-bed orientations has indicated consistent palaeocurrent directions over an area of 150,000 km^2 (Gellatly, Derrick and Plumb, in prep.). Attempts to reconstruct the depositional environment have prompted this investigation of possible conditions for the development of comparable widespread marine cross-bedding.

Terminology

Large-scale asymmetric sand ridges are generally termed "megaripples" or "sand waves"; "dunes" and "large scale ripples" have also been applied. There appears to be a continuous gradation in wavelength between those that have been termed megaripples (ca 0.7 to 15 metres) and those termed sand waves (15 metres to a maximum reported of about 1000 metres). The lower limit of megaripples (0.7 metres) coincides with a minimum value in the frequency distribution of ripple wave-lengths (Allen, 1963). Those in King Sound have wave-lengths mostly less than 10 metres and are here called megaripples.

Cross-bedding

Most studies of cross-bedding in recent sediments deal with fluviatile (Wolman and Leopold, 1957; Harms et al., 1963), deltaic (McKee, 1939, Fisk, 1961), beach (Thomson, 1937; McKee, 1957a), or estuarine point bar deposits (Land and Hoyt, 1966). Few studies of cross-bedding have been made on comparable modern tidal channel or marine deposits, partly because of difficulties of observation.

Experimental studies on the formation of cross-bedding, notably by Gilbert (1914), McKee (1957, 1965), McKee and Sterrett (1961), Simons, Richardson, and Nordin (1965), Allen (1965), and Jopling (1967), simulating conditions in rivers and deltas, have demonstrated the formation of cross-beds produced by a unidirectional current, but have not duplicated adequately the current regime in tidal environments, where the effects of both currents must be considered. Conditions in experiments of Simons, Richardson, and Nordin (1965) which produced megaripples with a wavelength of about 1 metre, apparently represent the closest experimental approach to the conditions in King Sound.

Megaripples and Sand Waves

Migration of large scale linguoid ripples and transverse megaripples (e.g. Allen, 1962) and of sand waves (Stride, 1963, 1965) is now generally considered to be responsible for the formation of most types of water-laid cross-bedding other than delta-bedding.

Megaripples and sand waves have been reported from several different environments, e.g. from rivers (Lane and Eden, 1940), from tidal estuaries (Cornish, 1901; Kindle, 1917; Van Straaten, 1953; Klein, 1964; Pettijohn and Potter, 1964; Swift and McMullen, 1968), and from shallow seas (Newell and Rigby, 1957; Jordan, 1962; Stride, 1963; Cloet, 1964; Imbrie and Buchanan; Hoyt, 1967;).

In these examples the external form has been described from

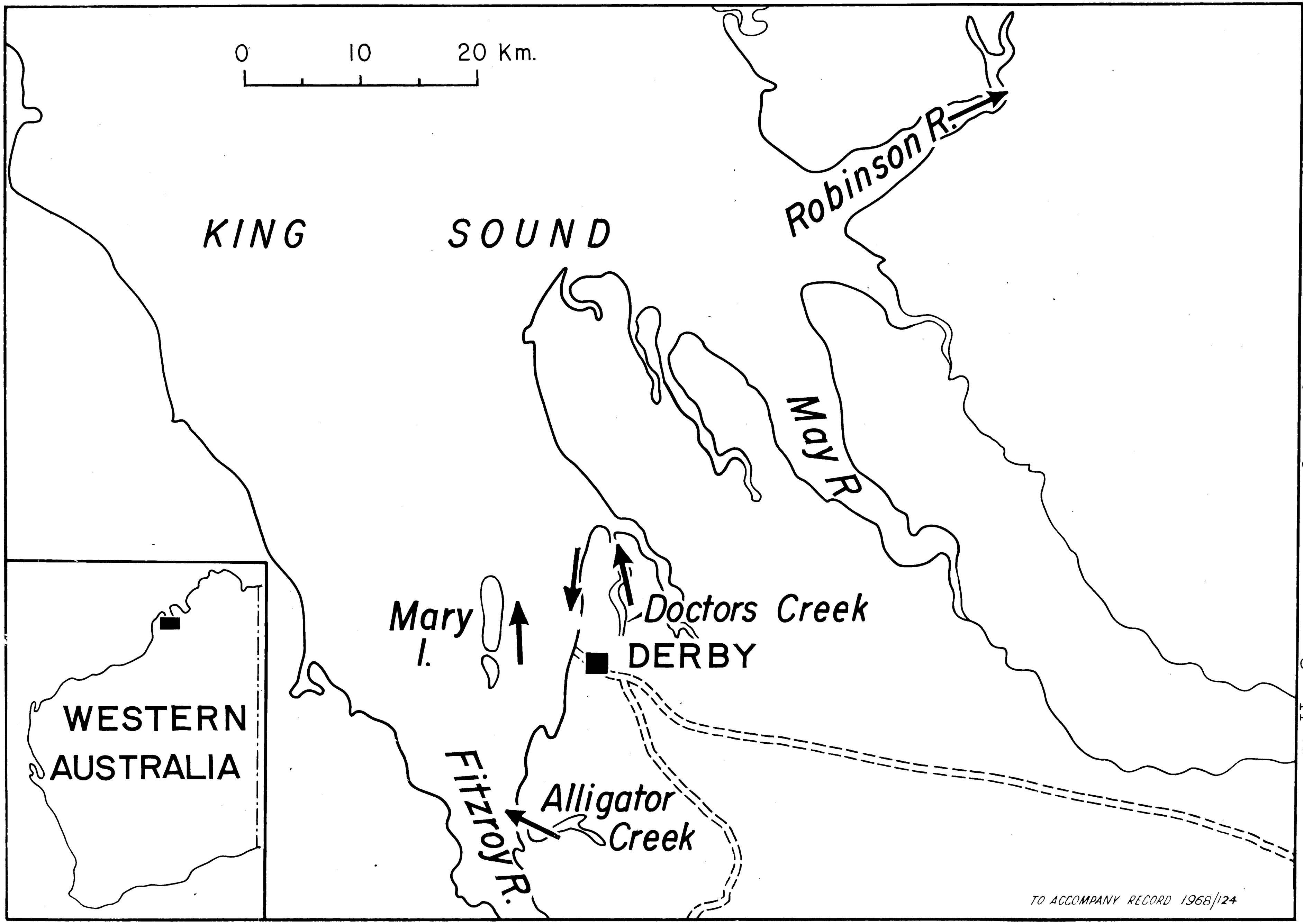

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Figure 1. Locality map showing facing directions of megaripples

visual observation, or has been outlined from depth soundings. Cross-bedding has been assumed, e.g. by Stride (1965), but has been reported from estuarine or marine sand waves, only in a core from seas near the Central Georgia coast (Hoyt, 1967), and in cores from the Bahama Banks (Imbrie and Buchanan, 1965).

The megaripples of King Sound are exposed at low tide, as a result of the high (35 feet) tidal range, and thus present an opportunity to study their internal structure, and to test the theory of the formation of widespread marine cross-bedding by megaripple migration.

KING SOUND SEDIMENTS

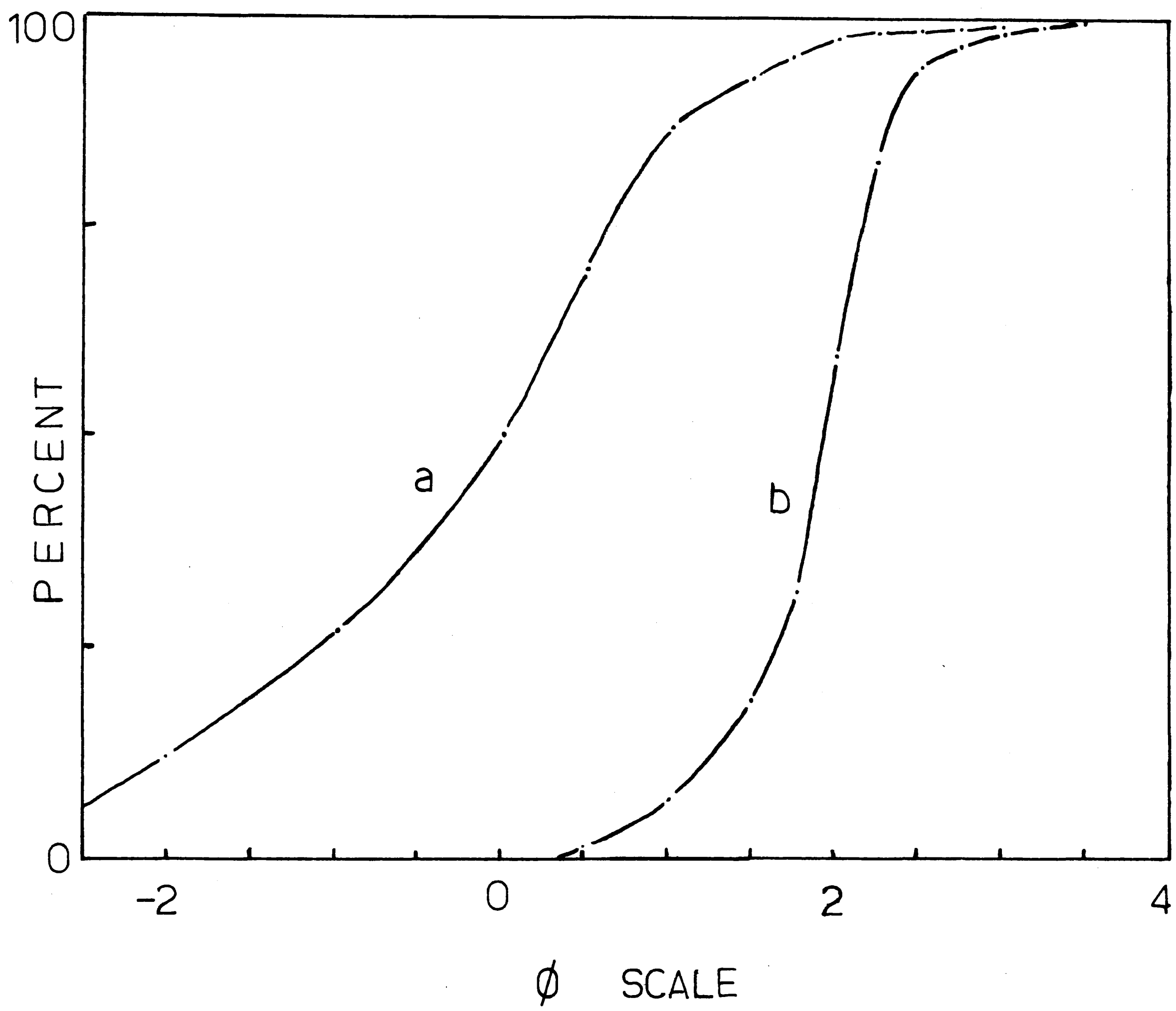
King Sound is part of a recently drowned (J.N. Jennings, pers. comm.) coastal lowland in which deposition of muds is taking place on tidal flats, and coarse sand, small pebbles, and shell fragments are being deposited and continuously reworked in the tidal channels. Intermediate grades of sediment are apparently deposited only further out to sea.

The sediment is supplied by the Robinson, May, and Fitzroy Rivers from source areas of predominantly Precambrian and upper Palaeozoic rocks: sandstones, granites, and porphyritic acid volcanics provide most of the clastic material.

Tidal scouring of the mud-flats has resulted in the formation of tidal channels with only muds in their catchment areas, yet containing shoals of coarse sand on the channel bottoms. These sand shoals lie directly on top of estuarine muds, and have well-developed megaripples.

Both sorting and grain-size of the sands vary widely, and appear to have had little control in the development of the megaripples, provided that coarse sand predominates. Because of this no detailed work has been carried out on grain-size distribution. Sorting curves for two grab samples are given in Fig.2. The specimen from Alligator Creek is finer-grained and apparently better sorted than most. That from King Sound, which probably represents the average grade and degree of sorting, has a median diameter of 1mm. Sediment in the

<u>**FIGURE 2**</u>



Cumulative frequency sorting curves for sands from King Sound: (a) Fitzroy estuary, (b) Alligator Creek.

Robinson estuary, although dominantly of coarse sand, contains much silt and is apparently more poorly sorted than in the other localities. Maximum pebble size is mostly around 2 cm., though this is exceeded locally.

THE MEGARIPPLES

The megaripples have wavelengths that range from 6 feet up to 30 feet, and amplitudes from 8 inches to 3 feet. The foreset slopes dip down current at 20° to 35°, and the topset slopes dip upstream at 2° to 10°. Morphological details of some typical examples are given in Table I. The topset surfaces have broad troughs and rises with axes parallel to the current direction, and thus the crest of each individual megaripple has irregular elevation, and the foreset slope has an irregular trend due to slight localised differences in the rate of advance.

A correlation is commonly found between the height of megaripples and the depth of water in which they have formed (e.g. Allen, 1963). In the King Sound area the megaripples have heights mostly in the range 0.5 to 1 metre, and have formed in water of mean depth 5 metres, and thus correspond closely to the general pattern of heights and water depths observed for other areas.

Small scale, asymmetric, flat-topped ripples with wavelengths mostly between 10 cm. and 20 cm. are common on the topset surface of the megaripples in Doctors Creek inlet, 5 km north of Derby, but are rare in the open waters of the Fitzroy estuary. The trends of these ripples are slightly sinuous, but in general parallel the crests of the megaripples. All variations are found in wavelength between these small-scale ripples and the megaripples, but wavelengths of between 0.5 metres and 1 metre are rare. Transverse and interference small-scale ripples, which were found by Klein (1964) on the topset slopes of megaripples in the Bay of Fundy, have not been observed on the megaripples of King Sound, but are present locally on the margins of the mudflats.

The presence or absence of small-scale ripples on the stoss sides of the megaripples is controlled mainly by current velocity. According to Simons, Richardson and Nordin (1965) the small scale

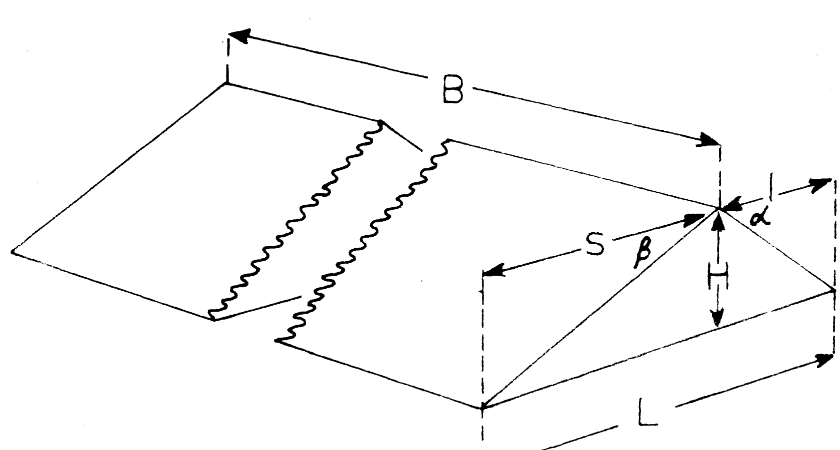
Table 1.

Morphological Elemants of Megaripples from King Sound

Locality	H	L(s+l)	B	s	l	α	β
Doctors Creek inlet	0.7	4.3	>10	3.0	1.3	30°	6°
Doctors Creek inlet	0.3	2.0	-	1.5	0.5	34°	7°
Doctors Creek inlet	0.5	3.7	>20	2.5	1.2	32°	8°
Fitzroy estuary	0.8	5.6	>20	4.5	1.1	34°	8°
Fitzroy estuary	1.0	7.4	-	6.	1.4	35°	3°
Robinson estuary	0.7	10.	-	8.	2.0	20°	5°

All dimensions are in metres. Data from field observations and from photographs.

Explanation of Symbols in Table 1 (After Allen, 1963).



ripples disappear with increasing current velocity. Also they disappear more readily in poorly sorted than in well sorted sand, and more readily in coarse than in fine sand, and do not form at all when the median diameter exceeds 0.6mm. Harms and Fahnestock (1965) note that they disappear with increase in the amount of sediment in transport. Thus higher current velocities with resulting increases in grain size and in the amount of sediment transported are probably responsible for the paucity of small scale ripples in the Fitzroy estuary.

Pebbles up to about 2 cm., coarse sand grains, and shell fragments are concentrated on the topset surface through removal of finer material, and at the foot of the foreset slope due to rolling of the coarser material down the foreset slope.

Rill-marks, due to erosion by seepage water, scar some of the foreset slopes. Transverse streams of seepage water flowing in the foreset furrow cause minor erosion scours.

In most cases the crests of the megaripples are at right angles to the local shorelines and to the current direction, and have down-estuary-facing lee slopes indicating formation by the ebb tide. Those examined in the Robinson estuary have crests aligned at about 60° to the shore and foreset slopes that face up the estuary. Up-estuary facing megaripples have also been noted locally in the Fitzroy estuary and in the King Creek estuary in the southeastern corner of Secure Bay some 70 miles northeast of Derby. Figure 1 shows localities where megaripples have been examined, and the direction of facing.

The presence of both up-estuary and down-estuary facings of the megaripples is not unusual and reflects the mutually evasive nature of the paths of the flood and ebb tides, a situation noted previously by Van Straaten (1953) in the Bay of Arcachon, by Robinson (1960) in English estuaries, and by Klein (1968) in the Bay of Fundy.

Internal Form

The internal form has been investigated by trenches dug across the megaripples, and parallel to their crests. Most of the megaripples are cross-bedded with steeply dipping foreset laminae outlined by layers of coarse sand, and parallel to the lee slope. Foreset laminae are mostly about 5 cm. to 8 cm. thick, and foreset units are 15 cm. to 35 cm. thick. Most have straight-dipping foresets; some have gently curving foresets that gradually pass down-current into straight foresets (Fig.5a). Others have only very poorly defined cross-beds or are internally structureless. According to McKee (1957) curved foreset laminae are characteristic of higher current velocities than the straight ones.

In each locality several megaripples were sectioned, and dip directions of the foresets were found to be self consistent. No evidence was found of reversals of cross-bed directions due to local alternations of the current direction.

The only structure noted in trenches dug parallel to the crests was very gently undulating bedding due to variations in the height of megaripple crests. No evidence of festoon-type scallops was found.

Preservation

Time available permitted only a single visit to each locality and thus it is not known whether the megaripples are completely destroyed by the flood tide, and if so, whether they are temporarily replaced by upstream facing megaripples. Observation of early erosion by the incoming tide in the Fitzroy estuary suggests at least partial destruction. Probably only slight modification results rather than complete destruction, since the maximum velocity path of the flood tide rarely coincides with that of the ebb, and since Stride (1963) has shown that asymmetry of sand waves can both develop and be preserved in areas with only a 0.1 knot difference between the velocities of the opposing tides. Also, evidence from the Robinson estuary where successive stages of advance of individual megaripples can be recognized without evidence of intervening periods of erosion, suggests only minimal modification by the weaker tide.

Since the megaripples advance with successive tides, it is unlikely that they will be permanently preserved except at times of extreme river flood, when the supply of sediment is great. During river flood periods any destructive effect of the flood tide would be minimised by the opposing river flow, and the influx of fresh sediment could bury the earlier-formed megaripples.

Current Velocities

There is little information available at present on tidal current velocities in King Sound. Currents of 2 knots have been noted at Derby wharf by the resident harbour engineer, but this value is probably exceeded elsewhere in the estuary. A velocity of 7 knots has been noted in the Victoria River, N.T., (I.R. Pontifex, pers. comm.). This occurs in narrows in the upper parts of the estuary and is not likely to be attained in the lower wider parts, but demonstrates that tidal currents may attain high velocities locally in northwest Australia.

The size of pebbles transported by the tidal currents in King Sound, when related to the curves of Hujlström (1935) suggest surface currents of about 150 cm/sec. (3 knots).

In the open sea current velocities are likely to be lower than in confined tidal estuaries, but currents of 3 to 4 knots are known from the Gulf Stream some 500 km. from the Georgia coast (Richardson, et al., 1963), and currents of 1 to 2 knots have been reported from the North Sea, and 3 knots from the Straits of Dover (Stride, 1963).

Rate of Migration

Measurement of the rate of migration was outside the scope of the present study, and estimates are thus tentative. In a more lengthy study measurement of the migration rate would probably be feasible, particularly in the narrow tidal inlets.

The only direct evidence of the rate of megaripple migration in the King Sound area comes from the Robinson estuary. Here silt layers, presumably deposited at slack water, are intercalated with the sand foreset laminae, and are about 0.5 metres apart. This suggests a migration rate of about 1 metre per day. A higher rate of migration would be expected in the more open waters of the Fitzroy estuary where the sediment is coarser and current velocities presumably higher. The above figures are comparable with a movement of 3 metres per day for megaripples of gravelly sand in a part of the Bay of Fundy with a tidal current velocity of 1.5 knots (Klein, 1968), and also to rates observed by Cornish (1901) for megaripples in British estuaries.

Allowing for the fact that the megaripple migration takes place during only part of each tidal cycle, the figures are also similar to the average migration rate of 5 metres per day noted in the Mississippi River by Lane and Eden (1940).

OTHER AUSTRALIAN MEGARIPPLES AND SAND WAVES

Megaripples of the type described in this paper are probably developed at other localities around the Australian coast, particularly in the northwest where strong tidal currents prevail. Examples have been noted in the Victoria River estuary, Northern Territory, by I. Sweet (pers. comm.). Also, an example of asymmetrical sand waves parallel to the local shoreline has been noted by P.R. Dunn (pers. comm.) from air-photographs of Boucaut Bay about 200 miles east of Darwin. These sand waves are submarine features with an average wave-length of about 350 feet. The steep side faces shorewards. They have been formed apparently by the action of waves and/or tidal currents on sediment supplied by westerly long shore drift from the south of the Blyth River immediately to the east.

Other examples of tidal megaripples have been noted in St. Vincent Gulf, South Australia (Sprigg, 1965), and Lake King, Victoria (J.N. Jennings, pers. comm.).

Examples of transverse megaripples developed on point bars on the Murrumbidgee River, New South Wales, have been noted by Conybeare and Crook (in press), at Boundary Bend on the Murray River near the Victorian-South Australian border (J.N. Jennings, pers. comm.), on the Alice and Maranoa Rivers in Queensland (M.C. Galloway, pers. comm.), and no doubt exist on many other Australian rivers. Also cross-bedded large scale linguoid ripples have been noted by the writer in the Maitland River, Western Australia following a flash flood.

DISCUSSION

The assumption (e.g. by Stride, 1963 and Allen, 1962) that asymmetric marine sand waves and megaripples are internally cross-bedded is supported by the general occurrence of well developed cross-beds in the megaripples of King Sound. However, information is lacking on the effects of reversal of current, and on the rate of migration, not only in King Sound, but in almost all other areas. Stride (1963) has noted the presence of large asymmetric sand waves in the southern bight of the North Sea in an area where currents reach 2 knots, but where there is only a 0.1 knot difference between the velocities of the flood tide and the ebb. In areas such as this one might expect modification of the asymmetry during the lower velocity ebb tide, and eventual preservation at least locally of cross-beds indicative of reversed current directions. The absence of reversals of cross-bed facings in King Sound is surprising, but it does permit the tentative conclusion that the external form of megaripples and sand waves, even in an area of alternating current directions, is a reliable indicator of the facing of cross-beds within them. The variation in the direction of facing of the foreset slopes of the megaripples noted in King Sound and in other areas provides a suitable model for the development of reversals of current directions in cross-bedded sequences.

McKee and Sterrett (1961), referring to shoreface deposits and longshore bars, comment that "the present lack of information concerning primary structures in modern deposits makes impossible any detailed systematic comparison between them and their supposed counterparts in the laboratory". This statement is equally true concerning megaripples in tidal areas.

Experimental studies are required to detail the processes of destruction of cross-bedded megaripples by a reversed current, and incipient formation of those resulting from the new current direction. Although this study has shown uniformity of facing within each megaripple, this may not be so in other areas. Further studies of estuarine megaripples and coring of submarine sand waves would thus be of interest.

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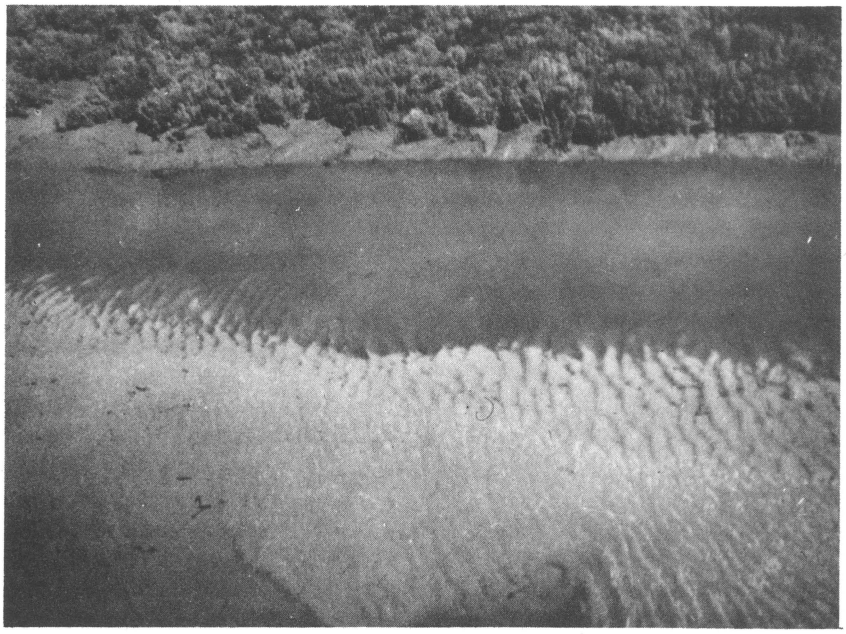
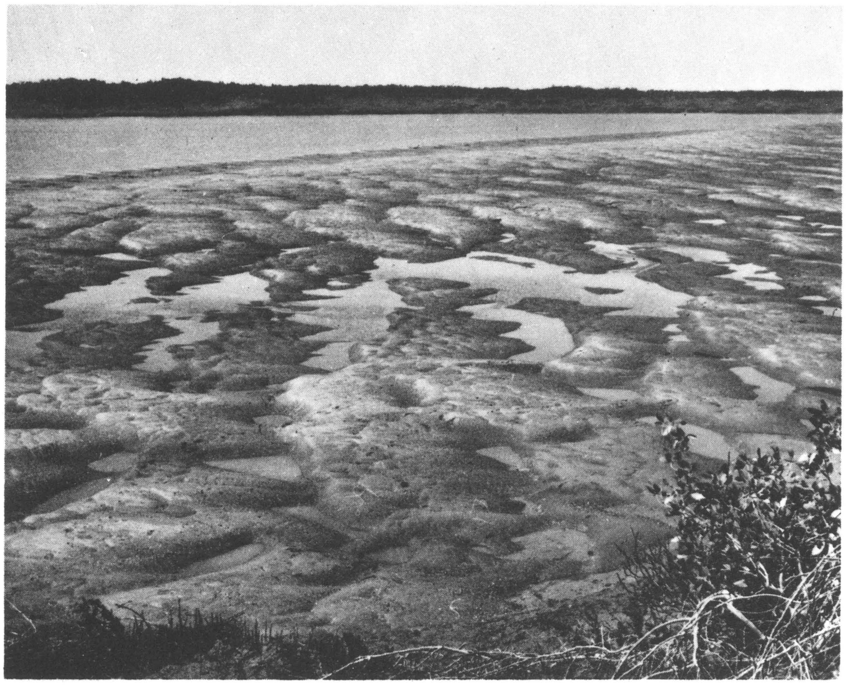


a. Aerial view of asymmetric tidal channel megaripples. King Creek estuary, Secure Bay, Yampi 1:250,000 Sheet area. (GA 1071)



b. Tidal megaripples in Doctors Creek inlet, 3 miles north of Derby. (M/541/4)

PLATE I

a. Tidal megaripples in Doctors Creek inlet, 3 miles north of Derby. (M/540/12)

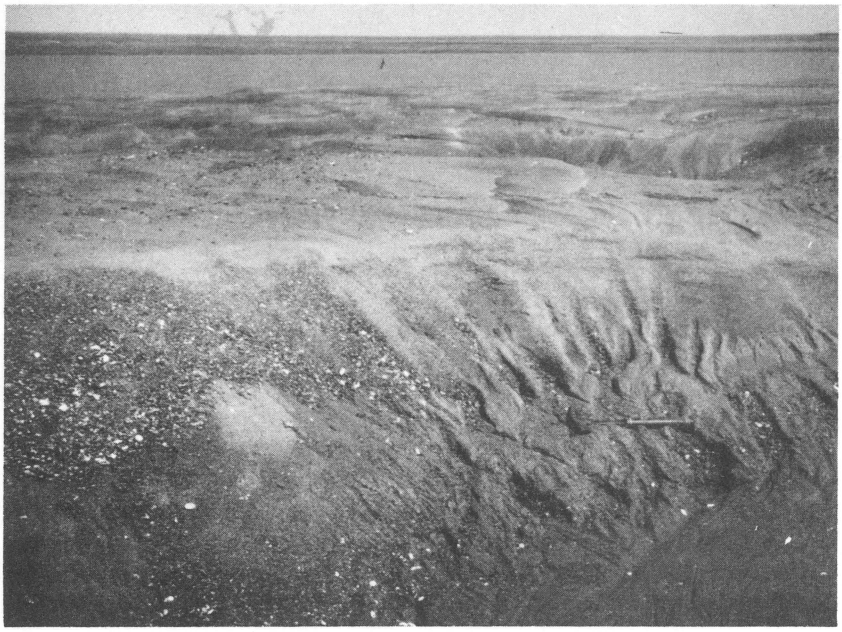
b. Tidal megaripples, King Sound, 1 mile east of Mary Island. (GA/962)

PLATE 2

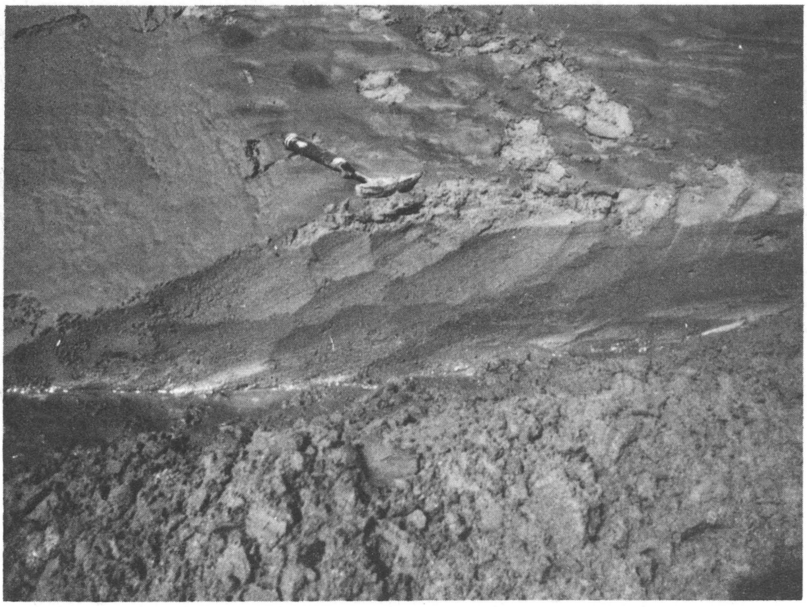
a. Large scale trough-shaped scallops in tidal megaripples, King Sound, 1 mile east of Mary Island. (GA 1067)

b. Erosion of tidal megaripples by transverse stream, Doctors Creek inlet. (M/537/6)

PLATE 3



a. Rill development on lee slope of megaripple, due to erosion by seepage water: King Sound, 1 mile east of Mary Island. (GA 1066)



b. Cross-bedded tidal megaripple, Robinson River estuary, $\frac{1}{4}$ mile north-west of Round Hill. (GA 1070)

PLATE 4

a. Cross-bedded tidal megaripple, Doctors Creek inlet. Foreset laminae show a gradation from curved to straight. (M/537/8)

b. Cross-bedded tidal megaripple with straight foreset laminae, Doctors Creek inlet. (M/537/11)

PLATE 5

a. Cross-bedded tidal megaripple, King Sound, 1 mile east of Mary Island. (GA/960)

b. Cross-bedded tidal megaripple, King Sound. (GA/964)

PLATE 6