Sedimentology (1985) **32**, 167–194

Hummocky cross-stratification, tropical hurricanes, and intense winter storms

WILLIAM L. DUKE*

Department of Geology, McMaster University, Hamilton, Ontario, Canada L8S 4M1

ABSTRACT

Most previous workers have inferred a storm origin for hummocky cross-stratification, which typically occurs in shallow-marine deposits. On the modern Earth, the only storms capable of profoundly affecting shallow-marine depositional environments are severe tropical cyclones (hurricanes) and mid-latitude winter wave cyclones (intense winter storms).

This paper examines the palaeogeographic distribution (including palaeolatitude and palaeogeographic setting) of 107 occurrences of hummocky cross-stratification, ranging in age from the Proterozoic to Recent. In each of these stratigraphic units, both palaeolatitude and palaeogeography are consistent with a direct storm influence (associated with the passage of hurricanes or winter storms directly over the site of deposition). This palaeogeographic evidence lends support to the inferred storm origin for hummocky cross-stratification; further, the distribution of the structure suggests that most occurrences (73%) were generated by tropical hurricanes, the remaining 27% being generated by intense mid-latitude winter storms. The preferential generation of hummocky cross-stratification by hurricanes is consistent with: (1) the known differences in the nature of the bottom flows generated by the two major storm types, and (2) the inferred nature of the flows which form hummocky cross-stratification. Hurricanes couple less effectively with the water column than do intense winter storms. Due to this ineffective coupling, hurricane-generated bottom flows tend to be oscillatory- or multidirectional-dominant, with only minor unidirectional components of motion. In contrast, intense winter storms generally do couple effectively with the water column, generating bottom flows which possess a dominant or significant unidirectional component. Most previous workers have suggested that hummocky cross-stratification forms under oscillatory- or multidirectional-dominant flow; thus, it is conceptually reasonable that the vast majority of ancient occurrences of hummocky cross-stratification were probably hurricane-generated, as suggested by the aforementioned palaeogeographic distribution.

The Proterozoic, Palaeozoic, Neogene, and Quaternary were times when global climate was similar to that of today. The distribution of hummocky cross-stratification deposited during these times suggests that both hurricanes and intense winter storms occupied latitudinal belts during these times which were essentially identical to those occupied by their modern counterparts.

The Mesozoic and Palaeogene were non-glacial times when global climate was much warmer than that of today. The distribution of hummocky cross-stratification deposited during this interval suggests that hurricanes occurred more frequently at higher latitudes during non-glacial times than they do at present. The possibility of a broadened hurricane belt during the Mesozoic and Palaeogene is consistent with climatic considerations. A limited number of Mesozoic and Palaeogene rock units containing hummocky cross-stratification were deposited in palaeogeographic settings that preclude a direct hurricane influence; these examples were deposited in the middle latitudes, suggesting that intense winter storms continued to form hummocky cross-stratification in the middle latitudes during these much warmer times.

Some previous workers have suggested that tsunamis may be capable of generating hummocky cross-stratification. The palaeogeographic distribution of the structure does not support an origin due to tsunamis.

Lacustrine examples of hummocky cross-stratification reported herein are the first known non-marine occurrences; they suggest that storm effects strongly influence the sedimentary record of some lakes.

* Present address: Department of Geosciences, The Pennsylvania State University, University Park, Pennsylvania 16802, U.S.A.

INTRODUCTION

Gilbert (1899), in his study of the Silurian Medina Formation, was the first to recognize, describe, illustrate, and interpret the sedimentary structure now known as hummocky cross-stratification. Re-examination of the Medina in New York and Ontario (Duke, 1982b) has confirmed that the undulatory bedforms to which Gilbert referred are indeed examples of hummocky cross-stratification. Gilbert emphasized the significance of upward-domed lamination and of the three-dimensional form and scale of hummocks and swales. His pioneering interpretation of the structure as a shallow-marine indicator generated by large storm waves soon fell under criticism (Fairchild, 1901), and the significance of his observations went unnoticed for over half a century. The structure was re-discovered in the 1960s and 1970s. Campbell (1966) was the first modern worker to recognize the structure, which he termed large-scale truncated wave-ripple laminae. The preferred term, hummocky cross-stratification, was introduced by Harms *et al.* (1975, p. 87). Most twentieth century workers have advanced interpretations which are essentially similar to Gilbert's.

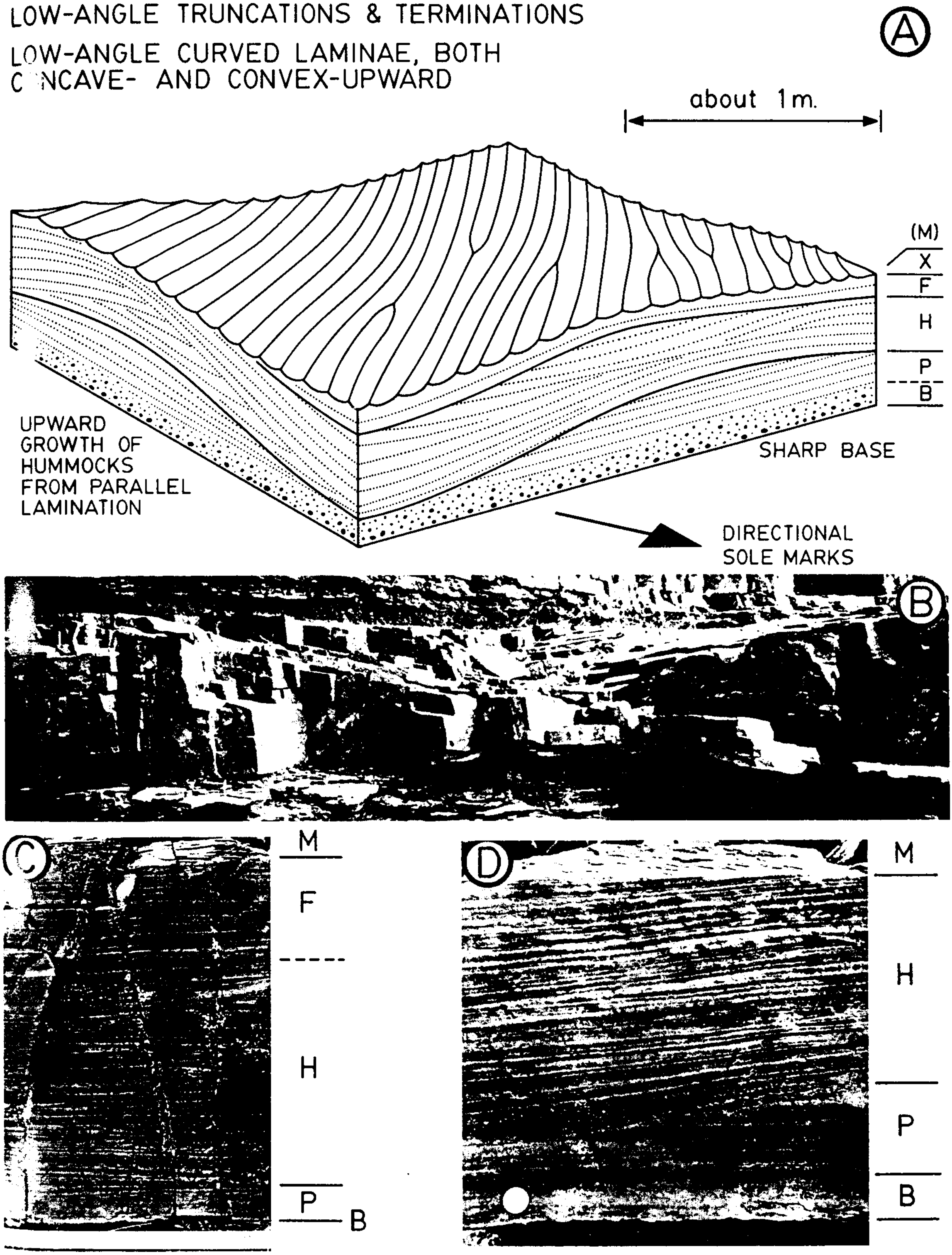
This paper has two main purposes: (1) to tabulate 107 known occurrences of hummocky cross-stratification, in order to establish a broader data base for research; (2) to compare the palaeogeographic distribution of these occurrences to the geographic distribution of major storms in the modern world. It will be demonstrated by means of this comparison that a probable genetic link exists between hummocky cross-stratification and both tropical hurricanes and intense winter storms. Further, this comparison suggests that the palaeogeographic distribution of major storms during non-glacial times differed somewhat from the geographic occurrence of their modern counterparts. A preliminary report has been presented elsewhere (Duke, 1982a).

In a separate study, Marsaglia & Klein (1983) examined the palaeogeographic distribution of 69 stratigraphic units containing inferred storm deposits (not necessarily containing hummocky cross-stratification). Of these examples, Marsaglia & Klein (1983, table 4) list 16 units which contain hummocky cross-stratification, but it should be noted that the Jurassic Fernie-Kootenay transition of western Canada is listed twice, and that there is no evidence for the presence of hummocky cross-stratification in the Cretaceous Kootenai Formation of Montana (W. C. James, 1983, pers. comm.). Marsaglia & Klein (1983) conclude that: (1) hummocky cross-stratification is formed primarily by intense mid-latitude winter wave cyclones, (2) a probable hurricane origin for the structure can be inferred for only one of the 14 examples, and, most importantly, (3) direct storm effects can be ruled out as the generative agent for hummocky cross-stratification in three examples. This last conclusion of their study implies that some agent other than storms may be responsible for the formation of hummocky cross-stratification in these and other examples (see further discussion below). Results of the present study, arising from a base of 107 units (including the 14 units of Marsaglia & Klein, 1983) are essentially different: (1) hurricanes are the primary inferred generative agents (73% of the examples), (2) intense winter storms probably formed hummocky cross-stratification in the remaining examples, and (3) all known examples of hummocky cross-stratification may be genetically attributed to direct storm effects associated with the passage of a major storm directly over the site of deposition.

HUMMOCKY CROSS-STRATIFICATION: DESCRIPTION AND PREVIOUS INTERPRETATIONS

Hummocky cross-stratification (Fig. 1) has never been observed during formation in natural environments; in fact, it has never been observed unequivocally in any recent sediments. Additionally, it has never been formed experimentally, although smaller structures with a similar morphology have been formed under oscillatory flows generated by laboratory apparata (Carstens, Neilson & Altinbilek, 1969; Lofquist, 1978;

Fig. 1. (A) Block diagram illustrating major morphological features of hummocky cross-stratification. Letters refer to ideal sequence discussed in text. (B) Sharp-based, hummocky cross-stratified sandstone, Cretaceous Cardium Formation, South Alberta. Note convex-upward hummocks separated by swale, parallel lamination overlying base, and growth of hummocks from parallel lamination. Field book (12 x 19 cm) gives scale. (C) Hummocky cross-stratified dolomitic sandstone, Proterozoic Johnnie Formation, SE California. Note sharp base overlain by divisions P, H, F and M. Scale in centimetres and inches. (D) Hummocky cross-stratified dolomitic sandstone, Proterozoic Johnnie Formation, SE California. Note sharp base overlain by apparently structureless sandstone (division B) followed by divisions P, H and M. Coin is 2·4 cm in diameter.


LOW-ANGLE TRUNCATIONS & TERMINATIONS
LOW-ANGLE CURVED LAMINAE, BOTH CONCAVE- AND CONVEX-UPWARD
A
about 1 m.
(M)
X
F
H
P
B
UPWARD GROWTH OF HUMMOCKS FROM PARALLEL LAMINATION
SHARP BASE
DIRECTIONAL SOLE MARKS
B
C
M
F
H
P
B
D
M
H
P
B

Southard, 1984). Consequently, in the absence of extensive laboratory and field data, virtually all that is known of the origin of the structure has been inferred from studies of ancient sediments.

Ancient examples of hummocky cross-stratification generally occur in coarse siltstone to fine sandstone; the structure is rarely observed in medium or coarse sandstone (Duke, 1984 and unpublished data). Occasionally, pebbles or cobbles are present within sandy laminae (Bourgeois, 1980; Duke, 1982b, fig. 5A; Walker, Duke & Leckie, 1983, fig. 4). Hummocky cross-stratified sandstones are characterized by gently curved, low-angle cross-lamination (Fig. 1). Within individual beds, curvature of laminae typically is both convex-upward (a 'hummock') and concave-upward (a 'swale'). Cross-strata dip at maximum angles less than about 10°–15°; higher-angle cross-stratification is extremely rare. Internally, intersections between laminae are varied: laminae may be erosionally truncated by overlying laminae, or may non-erosionally terminate against underlying laminae. Intersections may be either angular or tangential. In plan view, hummocks and swales generally are three-dimensional and radially symmetrical. Spacing (measured from hummock to hummock or swale to swale) is usually between 1 and 6 m. Typically, there is no preferred direction of cross-strata dip, nor does the angle of dip vary systematically with direction; consequently, vertical sections through hummocky beds appear very similar regardless of orientation.

Hummocky cross-stratified sandstones are commonly mantled with symmetrical ripples (Fig. 1). In some occurrences, hummocky sandstones are also associated with large, straight-crested conglomeratic symmetrical ripples possessing spacings of about 1 m (Wright & Walker, 1981; Leckie & Walker, 1982; Duke & Leckie, 1984; Leckie & Duke, 1984).

There appear to be three major associations involving hummocky cross-stratification:

(1) Interbedded lithologies

In this association, hummocky cross-stratified sandstones are interbedded with shale or mudstone (either terrigenous or carbonate mud). Sandstones are sharp-based and range in thickness from about 10 to 200 cm; the fine-grained interbedded material commonly is extensively bioturbated. Dott & Bourgeois (1982) formulated an idealized sequence for these sandstone/mudstone couplets; Walker, Duke & Leckie (1983) suggested a modified sequence of divisions (Fig. 1) which, in descending order, consists of:

M—mudstone, commonly bioturbated;
X—ripple cross-lamination. Ripples are usually symmetrical;
F—'flat' lamination, often gently undulatory;
H—hummocky cross-stratification;
P—planar parallel lamination;
B—basal division, consisting of one or more of the following: sharp base; oriented directional sole marks; basal lag of pebbles, shells, or rip-up clasts of mudstone; a graded or apparently structureless basal zone.

Walker *et al.* (1983) suggested that this sequence of divisions probably indicates initial deposition of sediment from a powerful unidirectional current (divisions B and P). As this current subsides relative to wave-generated oscillatory flow, the upper divisions of the sand bed (P, H, F and X) are formed under oscillatory-dominant flow.

High-angle cross-bedding, indicating reworking by continuously-operating shallow-marine processes (fairweather waves, tidal currents, etc.) is absent from this association.

Occurrences of association 1 generally have been interpreted as representing an alternation between rapidly-emplaced storm-deposited sands and slowly-deposited hemipelagic muds, suggesting sedimentation in water depths below fairweather wave base but above storm wave base (e.g. Hamblin & Walker, 1979; Dott & Bourgeois, 1982; Walker *et al.*, 1983).

(2) Amalgamated sandstones

This association consists of numerous sharp-based hummocky sandstones as above. Each sandstone bed is in erosional contact with the underlying bed. Erosional surfaces can be traced many metres laterally, often across the entire width of outcrop. Erosion locally eliminates the upper parts of the previously emplaced sandstone/mudstone couplet; consequently, mudstone is only locally present, typically forming isolated lenses within an amalgamated, hummocky cross-stratified sand body several metres or tens of metres in thickness. Mudstone lenses such as these often display abundant bioturbation, indicating a long period of quiescence prior to emplacement of the overlying sand bed.

Occurrences of this association generally have been interpreted as representing an environment similar to that of association 1, but with more energetic and/or frequent storm events, possibly indicating shallower depth and/or closer proximity to source (e.g. Hamblin

& Walker, 1979; Dott & Bourgeois, 1982; Walker *et al.*, 1983). Deposition was probably still below fairweather wave base and above storm wave base.

(3) Swaley cross-stratified sandstones

The term 'swaley cross-stratification' was introduced informally by Duke (1980) to distinguish a variant of hummocky cross-stratification in which swales are preferentially preserved, and hummocks are rare or absent. Large thicknesses of planar parallel lamination are commonly present as lenses within occurrences of this association. A description is provided by Leckie & Walker (1982).

Generally, swaley cross-stratified sandstones do *not* show evidence of amalgamation. Mudstone lenses and bioturbation are absent or extremely rare, and erosional contacts cannot be traced more than a few metres. Lenses of trough cross-bedded sandstone are present locally. Sedimentation apparently was largely continuous, not episodic as in associations 1 and 2.

The origin and environmental significance of swaley cross-stratification are unclear. All known occurrences are closely associated with more 'traditional' varieties of hummocky cross-stratification (associations 1 and 2), suggesting a related genetic process probably involving storm waves. In prograding shoreline sequences, swaley cross-stratification (where present) always overlies hummocky cross-stratification, and typically lies immediately below beach deposits. This typical pattern of facies sequences led Leckie & Walker (1982) to suggest an origin due to storm waves in water shallower than that for hummocky cross-stratification, and probably shallower than fair-weather wave base.

In summary, most previous workers have inferred an origin for hummocky cross-stratification involving storm-generated progressive surface gravity waves (e.g. Gilbert, 1899; Harms *et al.*, 1975; Hamblin & Walker, 1979; Walker, 1979; Bourgeois, 1980; Kreisa, 1981; Wright & Walker, 1981; Dott & Bourgeois, 1982; Harms, Southard & Walker, 1982; Hunter & Clifton, 1982; Leckie & Walker, 1982; Mount, 1982; Swift *et al.*, 1983; Walker *et al.*, 1983; Duke, 1984; Duke & Leckie, 1984; Leckie & Duke, 1984; Southard, 1984). Most of the preceding authors have specifically inferred an origin due to powerful oscillatory-dominant or multidirectional flows. Despite uncertainty regarding the dynamics of formation, hummocky cross-stratification is now widely regarded as perhaps the best indicator of a storm influence in ancient sedimentary sequences; however, there have been surprisingly few attempts to determine the nature of the storms that generated ancient occurrences of this structure (see below).

OCCURRENCES OF HUMMOCKY CROSS-STRATIFICATION

Tables 1, 2 and 3 (see Appendix) list all deposits known to the author to contain thicknesses of hummocky cross-stratification in excess of about 1 m. This thickness requirement eliminates units that contain rare, thin hummocky beds in a sequence dominated by other structures. Many of these examples have not been reported previously.

Of the 107 examples listed in the tables, 71 have specifically been identified in the literature as containing hummocky cross-stratification, or have been examined in the field by this author (or others where indicated) and are thereby known to contain the structure in abundance. These examples are indicated in the tables by the letter 'H' in the fourth columns.

An additional four examples have been reported as large-scale truncated wave-ripple laminae, an older term synonymous with hummocky cross-stratification. These are indicated in the tables by the letter 'T'.

Twenty-eight more examples have been illustrated and/or described in the literature in sufficient detail to permit the tentative recognition of hummocky cross-stratification ('I' in Tables 1, 2 and 3). In each instance the author(s) have invoked an origin involving storm effects. These examples include several tentatively recognized recent occurrences (Table 3).

The remaining four units were described by Goldring & Bridges (1973) as 'sublittoral sheet sandstones' (indicated in the tables by the letter 'S'). These authors actually report a total of 13 examples, but nine of these have been identified independently as exhibiting abundant hummocky cross-stratification ('H' or 'I'). I suggest that the remaining four probably also exhibit hummocky cross-stratification.

DETERMINATION OF PALAEOLATITUDE OF HUMMOCKY CROSS-STRATIFICATION

Figure 2 shows the palaeolatitudinal distribution of units exhibiting hummocky cross-stratification. Palaeolatitude of each unit is given in the tables.

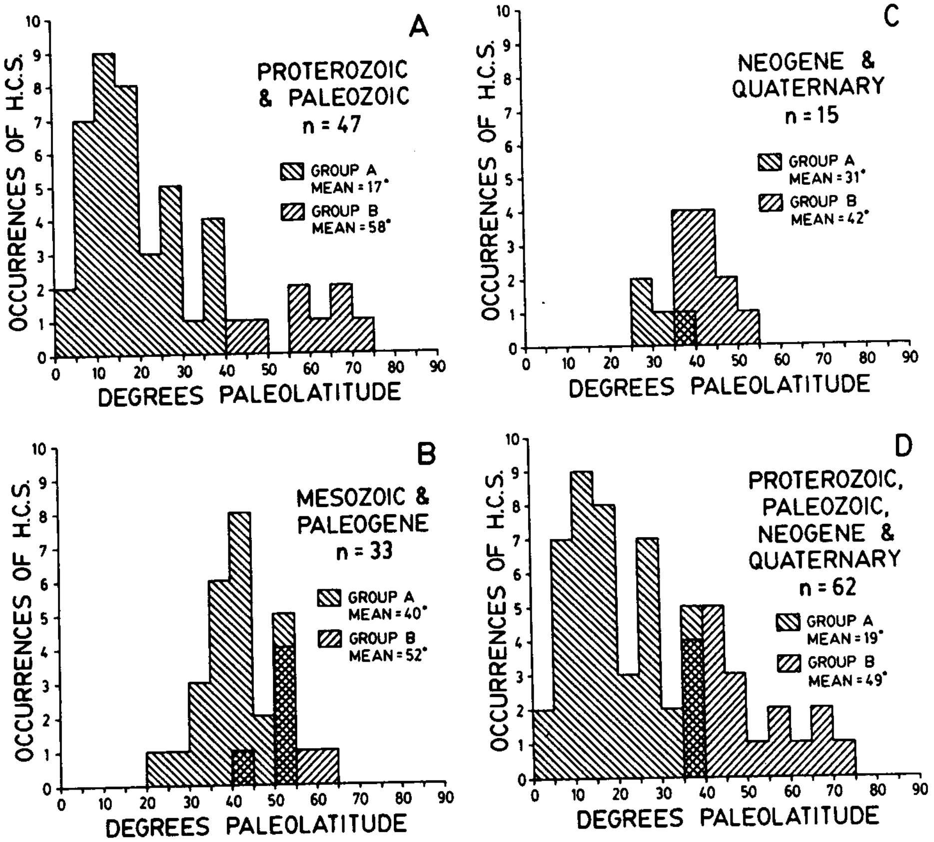


Fig. 2. Palaeolatitudinal distributions of units exhibiting thick sequences of hummocky cross-stratification. Group A examples are inferred hurricane deposits. Group B examples are inferred deposits of intense winter storms. These groups are differentiated on the basis of palaeogeographic setting (see Fig. 5). Note that overlap between group A and group B examples is indicated with cross-hachure. (A) Proterozoic and Palaeozoic rock units. (B) Mesozoic and Palaeogene rock units. (C) Neogene and Quaternary units (excluding Pleistocene Lake Bonneville deposits), (D) All units (except Pleistocene Lake Bonneville deposits) deposited during times when climate was similar to that of today.

Values for examples no older than Franconian (Late Cambrian) were interpolated from revised versions of the Palaeozoic maps of Scotese *et al.* (1979) provided by C. R. Scotese (1982, pers. comm.), the Mesozoic and Cenozoic maps of Smith & Briden (1977), and the present world map. Values of the older Cambrian and Dalradian examples were extrapolated from these reconstructions. No palaeolatitude is available for Proterozoic examples older than Dalradian other than the Athabasca Group, for which P. Ramaekers (1982, pers. comm.) has produced an estimate of 25°–30°. Differing ranges of palaeolatitude are represented by these examples; a mean value is given for each.

For certain examples, slight discrepancies exist between values of palaeolatitude reported herein and values reported by Marsaglia & Klein (1983). These differences are directly attributable to the manner in which palaeolatitude was determined. I interpolated between reconstructions where necessary. Marsaglia & Klein (1983) appear to have plotted their examples on the nearest reconstructed map.

MODERN STORMS AND THE INFERRED STORM ORIGIN OF HUMMOCKY CROSS-STRATIFICATION

The storm-wave origin for hummocky cross-stratification originally suggested by Gilbert (1899) has been reiterated with minor modification by many subsequent workers, as noted above. Most workers have not attempted to identify the type(s) of storm responsible for formation of these waves. Exceptions are Kaldi (1980), Kreisa (1981) and Mount (1982), who suggested tropical hurricanes as the generative agents for hummocky cross-stratification in the Lower Magnesian Limestone (Permian, England), Martinsburg Formation (Ordovician, Virginia), and Campito Formation (Cambrian, California), respectively.

Hummocky cross-stratification has most commonly been interpreted as a shallow-marine indicator (e.g. Gilbert, 1899; Harms *et al.*, 1975) formed below tidal and fairweather-wave influence (e.g. Goldring & Bridges, 1973; Hamblin & Walker, 1979). It has also been reported from lower estuarine sandstones (Campbell & Oaks, 1973), and glacio-marine shelf deposits (R. G. Walker, 1982, pers. comm.). Only one example of a thick sequence of non-marine hummocky cross-stratification is known to this author, formed in deltaic sands and gravels deposited at the Provo level of Lake Bonneville in Utah (R. Q. Oaks, Jr, 1982, pers. comm.). The significance of this latter example will be discussed in a later section.

The common occurrence of sharp-based hummocky cross-stratified sandstones in an open shelf setting many kilometres from shore (see Walker, 1979 and Walker *et al.*, 1983 for reviews) implies that the inferred generating storms were capable of extensive shoreline erosion, offshore transport of sand, and formation of waves much larger than fairweather waves. All of these require sustained strong winds acting over large areas of the sea. Storms that generate very strong winds include tornadoes, squall lines associated with thunderstorms, tropical hurricanes, and intense mid-latitude wave cyclones.

Tornadoes and squalls are localized in time and space, and are best developed over continental areas, not oceans (Riehl, 1965). Therefore, they are not capable of a profound impact upon shallow marine depositional environments. Severe tropical cyclones, formed during the warm season, are called hurricanes when they occur in the North Atlantic; for convenience, this name shall be used for all such storms. Extensive winds of hurricane force occur each winter in wave cyclones formed outside the tropics (Riehl, 1965, p. 166). Such storms will herein be referred to as 'intense winter storms' because their intensification to near- or full-hurricane force is restricted to the cold season. The term 'hurricane' will only be used for the severe summer cyclones formed within the tropics. Both hurricanes and intense winter storms are known to affect shallow marine depositional environments profoundly (see below). Both storm types are latitudinally restricted in the modern world. Palaeolatitudinal distributions of hummocky cross-stratification may be useful in determining an association between this structure and one or both of these storms in the ancient world.

Hurricanes and hummocky cross-stratification

Many studies indicate that hurricanes are capable of leaving a distinct imprint on marine deposits in the stratigraphic record (e.g. Hayes, 1967; Ball, Shinn & Stockman, 1967; Perkins & Enos, 1968). Because hurricanes are largely confined to low latitudes, Hayes (1967) suggested that their deposits may be useful palaeolatitude indicators.

Figure 3(A), the hurricane percentage–frequency distribution, has been constructed from data presented by Hayes (1967, table 1) for hurricane occurrence in the North Atlantic and western North Pacific. Equal weighting was given to the two data sets. The latitudinal distribution of hurricanes is similar in the southern hemisphere (Gray, 1968); however, many more hurricanes occur in the northern hemisphere than in the southern (Landsberg, 1960).

Figure 3(B) shows the latitudinal distribution of the surface area of Earth, also presented as a percentage–frequency distribution. Clearly, hurricanes occurring at low latitudes stand less of a chance of affecting the same site as do those occurring at higher latitudes, due to the larger area over which low-latitude hurricanes operate. It follows that Fig. 3(A) must be scaled by the distribution of Earth surface area (Fig. 3B) to produce the geologically significant hurricane percentage–density distribution (Fig. 3C). The hurricane percentage–density distribution is proportional to the latitudinal distribution of hurricane 'density' (i.e. number of hurricanes/unit area/unit time). This is the expected distribution of hurricane deposits from climates similar to that of the present. Employing a reasonable limit of 5% of the total density distribution, hurricane deposits may be expected from palaeolatitudes of about 10°–45° (Fig. 3C). (Note that I temporarily ignore the distribution of shallow seas, which must be considered for these shallow-marine deposits.)

If hummocky cross-stratification is generated solely by hurricanes, thick sequences dominated by this structure deposited during times when climate was

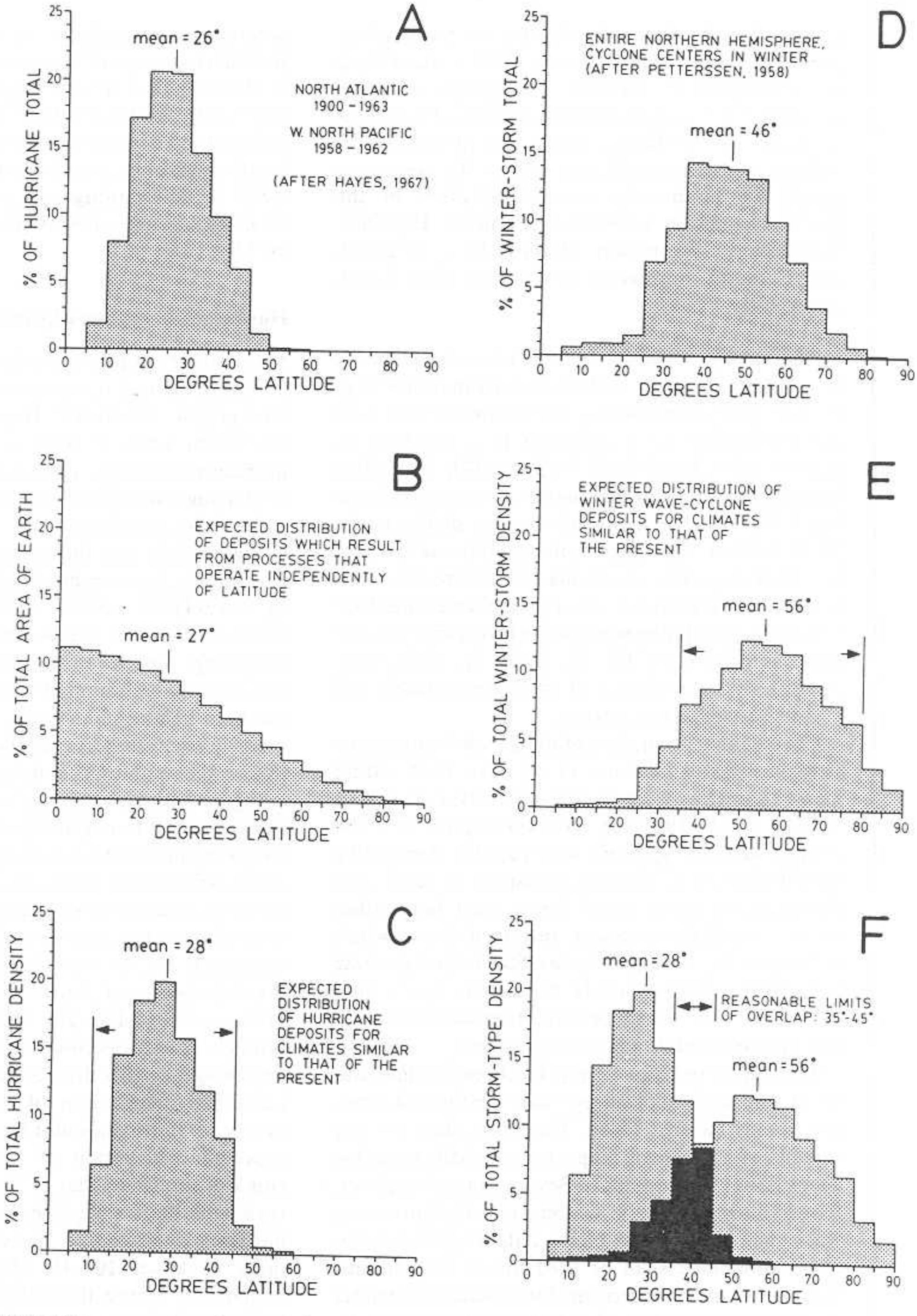


Fig. 3. (A) Hurricane percentage–frequency by latitude in the North Atlantic and western North Pacific, from data presented by Hayes (1967, table 1). See note on figure. (B) Percentage–frequency distribution of surface area of the Earth as a function of latitude. (C) Hurricane percentage–density distribution (proportional to the number of hurricanes/unit surface area/unit time) by latitude. Constructed from data in (A) and (B). Arrows indicate reasonable range of occurrence of hurricane deposits, based

similar to that of the present should show a distribution similar to that of Fig. 3(C). However, for times when climate was much different from that of the present, a different distribution might be expected. This possibility is discussed in a later section.

Intense winter storms and hummocky cross-stratification

Intense winter storms originate as wave cyclones in middle and high latitudes, forming along fronts between cold and warm air masses (Strahler & Strahler, 1979, p. 104). They may originate over continents or oceans. Those wave cyclones which either form at sea or pass from continents to oceans occasionally intensify to hurricane force (> 121 km hr^{-1}). They have generated exceptionally high surges and waves along extensive lengths of coasts (Riehl, 1965, pp. 166–168).

Data presented by Petterssen (1958, fig. 167) may be used to deduce the latitudinal percentage–frequency distribution of winter wave cyclones in the northern hemisphere (Fig. 3D). As with hurricanes, it is necessary to scale this distribution by the Earth surface-area distribution (Fig. 3B) to produce Fig. 3(E), the winter-storm percentage–density distribution (proportional to number of storms/unit area/unit time). These storms range from the equatorial belt to the pole; however, application of the 5% cutoff to the density distribution places reasonable limits on the expected range of winter-storm deposits (about 35°–80°). In the southern hemisphere, the winter-storm frequency peak is shifted about 10° poleward relative to the northern hemisphere distribution, and these storms are generally restricted to latitudes 40°–80°S (Petterssen, 1958, pp. 228–231).

If hummocky cross-stratification is generated solely by these storms, thick sequences dominated by this structure (deposited during times when climate was similar to that of today) may be expected from palaeolatitudes similar to those in which these storms occur today, roughly 35°–80°.

GLOBAL CLIMATE THROUGH TIME

Summarizing the palaeoclimatology review by Frakes (1979, especially pp. 260–263), it may be stated that only the interval embracing the Mesozoic and Palaeogene may unequivocally be considered a time of unusual warmth. The remainder of post-Archean time was characterized by lower temperatures similar to that of the present, except during cooler periods of more extensive glaciation. This broad picture of global palaeoclimatology suggests that a direct comparison between modern latitudinal storm belts and those of the ancient world is possible only when considered pre-Mesozoic, Neogene, and Quaternary examples. Non-glacial (Mesozoic and Palaeogene) climate was sufficiently different (warmer) than modern climate to make a direct comparison impossible. For this reason, I shall first consider the palaeolatitudinal distribution of hummocky cross-stratification only from times when climate was similar to that of today; examples from non-glacial times will be considered in a later section.

EXAMPLES OF HUMMOCKY CROSS-STRATIFICATION FROM CLIMATES SIMILAR TO THAT OF TODAY

As previously noted, global climate during the Proterozoic, Palaeozoic, Neogene, and Quaternary was generally similar to that of today, allowing the direct comparison of the latitudinal distribution of modern storms and the palaeolatitudinal distribution of hummocky cross-stratification deposited during these times.

Proterozoic and Palaeozoic examples of hummocky cross-stratification: discussion

The significance of the palaeolatitudinal distribution of Proterozoic and Palaeozoic hummocky cross-stratification is supported by the wide range of

upon a limiting value (> 5%) of the density distribution. (D) Percentage–frequency of wave cyclones by latitude in the northern hemisphere in winter, from data presented by Petterssen (1958, fig. 167). (E) Winter–storm percentage–density distribution (proportional to the number of wave cyclones/unit surface area/unit time) by latitude. Constructed from data in (D) and (B). Arrows indicate reasonable range of occurrence of winter-storm deposits, based upon a limiting value (> 5%) of the density distribution. (F) Comparison of the expected ranges of occurrence of hurricane deposits and winter-storm deposits. Overlap between the two percentage–density distributions is shown in black. Arrows indicate the expected range of overlap of the two distributions (35°–45°), based upon a limiting value (> 5%) of the density distributions. Note that if southern-hemisphere data were included in these figures, the hurricane distribution would be shifted slightly equatorward and the winter-storm distribution would be shifted slightly poleward, resulting in a more limited range of overlap.

localities and ages of the examples. The sample size if relatively large ($n = 47$). The Helikian examples from Canada are the oldest known occurrences of hummocky cross-stratification. Each of the periods of the Palaeozoic is represented. Examples are known from all continents except Antarctica.

The pre-Mesozoic distribution of hummocky cross-stratification is shown in Fig. 2(A). Immediately obvious is the low-latitude concentration of data points, and the wide palaeolatitudinal range of occurrences (4°–70°). Also notice that the data tend towards two separate peaks: a pronounced peak is present in the low latitudes; a smaller peak is present in the high mid-latitudes. Data fall into two groups. The group A points are from palaeogeographic settings which favour hurricane effects at the site of deposition. They form a low-latitude distribution (4°–39°) which is similar to that of modern hurricane density. The means and ranges of occurrence of these distributions are similar. It is consistent with these data to invoke a hurricane origin for the structure in group A examples.

It is noteworthy that these 39 examples attributed to hurricanes include the three examples which Marsaglia & Klein (1983) dismissed as being 'probably of different origin' (i.e. an indirect storm origin or a non-storm origin). These three examples are the Early Cambrian Campito Formation of California at 10°N (Mount, 1982) and two Late Cambrian units, the Jordan Formation of Wisconsin at 10°S (Bourgeois, 1980; R. H. Dott, Jr, 1982, pers. comm.) and the Nolichucky Formation of Virginia at 17°S (Markello & Read, 1981). These three examples are from hurricane-dominated palaeolatitudes, and careful examination of the palaeogeographic reconstructions (Fig. 4) suggests that none of these examples would have been sheltered from probable Cambrian hurricane paths (see explanation below). It is therefore not clear why Marsaglia & Klein (1983) dismissed a direct storm origin for these three examples; the original authors all suggested storm interpretations.

The palaeogeographic setting of the three Cambrian units dismissed by Marsaglia & Klein (1983) is compared to its closest modern analogue (North Africa) in Fig. 4. The climatological studies of Arnold (1966), Gray (1968), and Carlson (1969a, b) are summarized below and in Fig. 4(A). The arrows in Fig. 4(A) indicate typical paths of major wave perturbations developed in the upper easterly flow over present-day North Africa. These disturbances originate over the interior of the continent, and they commonly develop into tropical storms and hurricanes over the Atlantic. In fact, the majority of North Atlantic hurricanes originate from these disturbances.

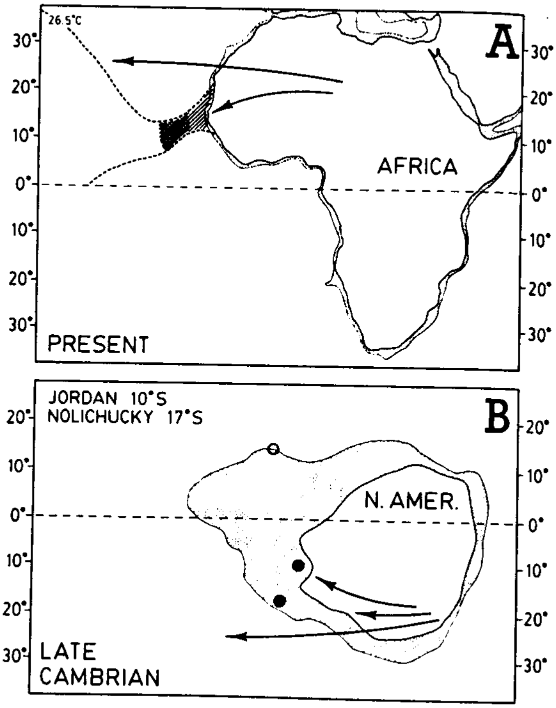


Fig. 4. Comparison of an ancient palaeogeographic setting (B) and the closest modern analogue (A). See text for explanation. (A) Present-day Africa, showing extent of the surrounding continental shelf (stippled area). The 26·5°C ocean surface-water isotherm for August in the North Atlantic is also shown. Arrows indicate typical paths of major wave perturbations in the upper easterly flow over the continent. When these disturbances cross the African coast in the vicinity of the Cape Verde Islands, they immediately intensify to tropical storm status (single-hatchured area) and often develop rapidly to full hurricane status within the double-hatchured area. (B) Late Cambrian reconstruction of North America after Scotese *et al.* (1979). In this reconstruction, the continent is rotated roughly 100° clockwise from its present orientation. Stippled area shows the areally extensive, warm epeiric sea surrounding the subaerial land mass. Arrows represent typical paths of hypothetical wave perturbations analogous to those formed over present-day North Africa. Filled circles indicate locations of late Cambrian Jordan Formation (Wisconsin) and Nolichucky Formation (Virginia) at 10°S and 17°S, respectively. Open circle indicates location of *Early* Cambrian Campito Formation (California).

Most wave perturbations follow an east–west route represented by the northern arrow in Fig. 4(A). Over the cold waters of the eastern North Atlantic, at approximately 15°–30°N, these disturbances maintain their identity as tropical depressions; once they cross the 26·5°C isotherm, however, they commonly intensify to hurricane status over the warm sea surface below, and continue on an east–west track toward the Caribbean and North America.

Many wave perturbations follow a more equatorial route represented by the southern arrow in Fig. 4(A). When these disturbances cross the African coast in the vicinity of the Cape Verde Islands, they immediately encounter warm ocean surface water enclosed by the 26·5°C isotherm. Commonly, these disturbances immediately intensify to tropical storm status (single-hatchured area in Fig. 4A) and often develop rapidly to full hurricane status within the double-hatchured area.

Figure 4(B) shows the Late Cambrian reconstruction of North America (after Scotese *et al.*, 1979). The stippled area shows the areally extensive epeiric sea surrounding the subaerial land mass. Arrows represent typical paths of hypothetical wave perturbations analogous to those formed over present-day North Africa. Due to restricted circulation in the very broad and shallow epeiric sea, wave perturbations generated over Late Cambrian North America would have undoubtedly encountered very warm ocean surface water immediately after crossing the coast, leading to rapid development of tropical hurricanes west of the subaerial land mass. Thus, the Late Cambrian units indicated in Fig. 4(B) were probably deposited along common hurricane paths, contrary to the conclusion of Marsaglia & Klein (1983).

The *Early* Cambrian Campito Formation of California (also rejected by Marsaglia & Klein, 1983) is indicated by the open circle on Fig. 4(B). Even when plotted on this reconstruction, the Campito is seen *not* to be sheltered from probable northern hemisphere hurricane paths originating on either side of North America. The extrapolated Early Cambrian reconstruction is even more favourable to direct hurricane effects at the site of deposition.

Thus, the three hummocky cross-stratified units dismissed by Marsaglia & Klein (1983) as being non-storm influenced or indirectly storm influenced are probably best interpreted as being directly influenced by hurricanes passing over the site of deposition. This interpretation is strongly supported by Dott's (1974) analysis of shallow-marine conglomerates from the Late Cambrian of Wisconsin, in which he demonstrated: (1) the presence of very large storm waves, and (2) the lack of a preferred direction of wave propagation toward the site of deposition. Random storm-wave approach favours the interpretation of local wave generation by storms, rather than distant generation of swell waves by storms or earthquakes (Dott, 1974).

Group B Proterozoic and Palaeozoic occurrences (Fig. 2A) are from palaeogeographic settings that preclude the encounter of strong hurricane effects, but are favourable to intense winter-storm effects. Group B occurrences form a mid-latitude distribution (40°–70°) which is similar to that of modern winter-storm density. The means and ranges of occurrence of these distributions are similar. It is consistent with these data to invoke a winter-storm origin for hummocky cross-stratification in group B occurrences. One example (the Permian of Australia) consists of a thick hummocky sequence containing numerous large glacial dropstones (R. G. Walker, 1982, pers. comm.). This indicator of cool surface water temperature is additional evidence against a hurricane influence. The palaeogeographic distinction between the group A and group B examples is illustrated in Fig. 5.

It should be noted that the palaeogeographic distinction between inferred hurricane-generated and winter-storm-generated occurrences of hummocky cross-stratification is not infallible. In particular, some of these examples may well have been influenced by both types of storm, and some of the examples classified as hurricane-influenced may possibly have been influenced primarily by intense winter storms. As suggested by Fig. 3(F), the range of ambiguity is probably confined to palaeolatitudes between about 35° and 45°. The same is true of the Neogene and Quaternary examples discussed below.

Hummocky cross-stratification is *not* restricted to the palaeolatitudes in which it occurs simply by the availability of shallow-sea depositional area. Figure 6 shows the latitudinal distribution of Palaeozoic shallow seas, compiled from the seven reconstructions of Scotese *et al.* (1979). This distribution closely resembles that of Earth surface area, suggesting restriction of the generative agents to the latitudinal belts of the occurrences by some mechanism other than availability of shallow seas. The relationship between continentality, shallow-sea area, and ancient weather disturbances will be discussed further by Duke (in prep.).

Neogene, Pleistocene, and possible recent examples of hummocky cross-stratification: discussion

Despite an extremely small sample size ($n = 15$), post-Palaeogene examples of hummocky cross-stratification (Fig. 2C) fall into two groups which clearly reflect their probable origin due to either hurricanes or

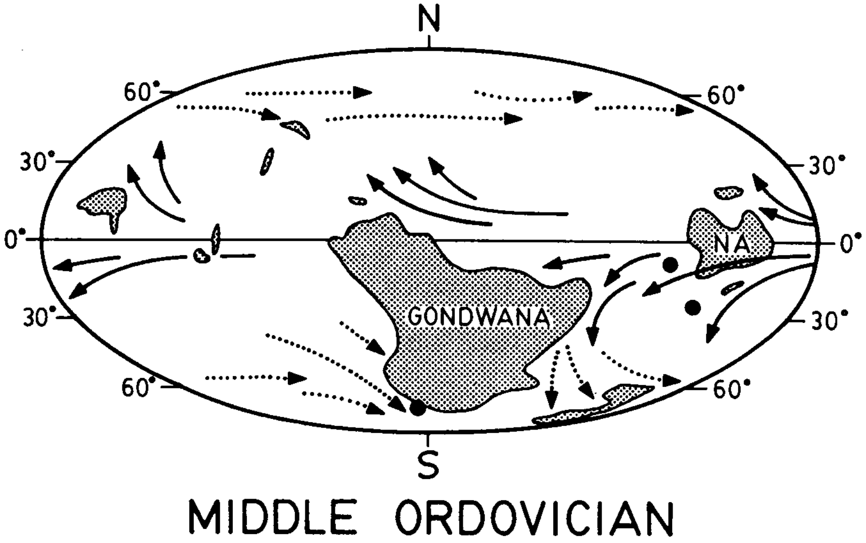


Fig. 5. Palaeogeographic reconstruction of the Middle Ordovician Earth (after Scotese *et al.*, 1979). Stippled areas represent subaerial land masses. Solid arrows are inferred summer hurricane paths; dotted arrows are inferred winter-storm paths. Filled circles represent examples of hummocky cross-stratified storm deposits. The two North American examples are the Kinnikinic Quartzite (9°S) and the Martinsburg Formation (26°S). These are inferred hurricane deposits. The Gondwana example is from the Ordovician of Jordan (70°S); these deposits are inferred to be influenced by winter storms only. Note that the palaeogeographic setting of the Jordanian example precludes any possible direct hurricane influence. Compare these hypothetical storm paths to those of the modern Earth (Strahler & Strahler, 1979, fig. 7.19).

intense winter storms (excepting the lacustrine example). Note that the very small sample size of the inferred hurricane-generated examples ($n = 4$) suggests that the mean of the distribution carries no real significance.

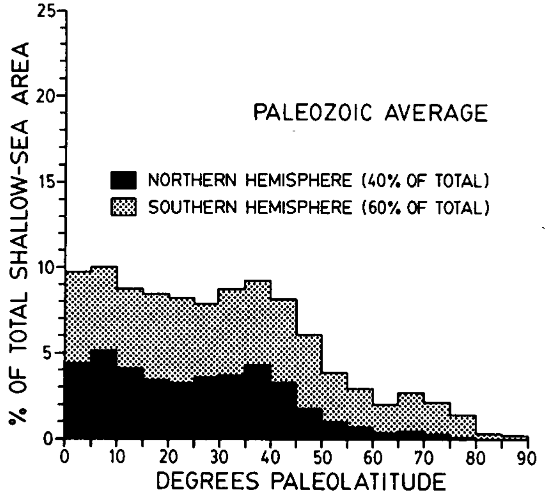


Fig. 6. Palaeolatitudinal distribution of Palaeozoic shallow-sea area, compiled from the seven palaeogeographic reconstructions of Scotese *et al.* (1979). The mean of this distribution is 30°.

I agree with Bourgeois (1980), who has suggested that probable Recent examples of hummocky cross-stratification have been recognized from various shallow-shelf settings. The geographic settings of these examples (see Table 3) strongly suggests that hummocky cross-stratification may be generated in the modern world by both hurricanes and intense winter storms.

ALTERNATIVE MECHANISMS FOR THE GENERATION OF HUMMOCKY CROSS-STRATIFICATION DURING TIMES OF GLOBAL CLIMATE SIMILAR TO THAT OF TODAY

It should be emphasized that palaeogeographic distributions cannot be used to establish unequivocally a genetic link between a sedimentary structure and a hypothetical process of formation. It is therefore prudent to consider other generative mechanisms for hummocky cross-stratification in the examples previously discussed.

Tsunamis have been suggested as one possible generative agent for hummocky cross-stratification (Goldring & Bridges, 1973; Dott & Bourgeois, 1982).

Tsunamis are generated in tectonically active areas; with the wide latitudinal drifting of continents over geologic time, the occurrence of tsunamis should not be latitudinally controlled. Thus, tsunami deposits should form a palaeolatitudinal distribution similar to that of the Earth's surface area (Fig. 3B). Therefore, if hummocky cross-stratification were the product of tsunamis only, the number of occurrences of this structure should be a monotonically decreasing function of palaeolatitude. The observed low-latitude peak in the number of occurrences (Fig. 2D), with values declining both poleward and equatorward, is inconsistent with a tsunami origin, but is consistent with the preferred storm origin. (Note, however, that palaeolatitudinal distribution cannot eliminate the possibility that tsunamis form a small percentage of examples of hummocky cross-stratification.) The same argument could be applied to any other hypothetical generative agent which operates independently of latitude.

Recently, Swift *et al.* (1983) commented upon the findings contained in a preliminary draft of this paper. They presented the following conceptual argument against formation of hummocky cross-stratification by hurricanes: 'Hummocky cross-strata have been attributed to hurricane-generated currents (Duke, in press). On the Atlantic Shelf, however, there is considerable evidence to indicate that the large mid-latitude storms couple more efficiently with the water column than the hurricanes which move up the shelf from the north equatorial zone. While hurricanes have much more intense winds in the center, the zone of elevated wind speed is only a fraction of the diameter of that of a mid-latitude storm, and these centres are so fast-moving that the shelf water column commonly is unable to come to equilibrium with the peak wind speed. Also, hurricanes are most frequent during the late summer and early fall, when the water column is highly stratified and the downward turbulent transfer of momentum is inhibited' (Swift *et al.*, 1983, p. 1304).

If we accept that hummocky cross-stratification is best interpreted as a storm deposit, and if we further accept that tropical hurricanes and intense mid-latitude winter wave cyclones are the only storms capable of profoundly affecting shallow-marine depositional environments, then the evidence presented herein inescapably indicates that the principal generative agents for hummocky cross-stratification are hurricanes, not winter storms. Thus, the *observational* evidence contained herein indicates a flaw in the *conceptual* reasoning of Swift *et al.* (1983). I suggest the following resolution to the conceptual difficulty:

Swift *et al.* (1983) are quite correct in their assertion that hurricanes couple less efficiently with the water column than do intense winter storms; I suggest it is precisely for this reason that hurricanes are more effective generators of hummocky cross-stratification. By coupling with the water column, a winter storm generates a powerful unidirectional current at the sediment–water interface; this unidirectional current overwhelms (or, at least, greatly modifies) the oscillatory or multidirectional flow generated by the accompanying surface gravity waves. The resultant flow is typically either unidirectional-dominant or at least very nearly so, as described by Swift *et al.* (1983). I suggest that this class of flow generates sedimentary structures which closely resemble those formed under purely unidirectional flow (e.g. trough cross-bedding). On the other hand, hurricanes do not effectively couple with the water column and therefore do not generate a strong unidirectional current at the bottom. Thus, the orbital water motion caused by the enormous surface gravity waves generated beneath hurricanes is the only source of strong fluid motion near the bottom; these waves form powerful oscillatory or multidirectional bottom flows which do not possess a strong unidirectional component. I agree with the majority of previous workers (see above) who suggest that hummocky cross-stratification is generated by powerful oscillatory or multidirectional flows such as those which form beneath hurricanes. In this regard, note that stratification of the water column beneath hurricanes *does* inhibit turbulent transfer of momentum by unidirectional flow; however, such stratification does *not* present a barrier to the oscillatory motion generated beneath surface gravity waves.

Swift *et al.* (1983) suggest an origin for hummocky cross-stratification due to flows which are either unidirectional-dominant or which possess a significant unidirectional component. This suggestion contrasts markedly with the conclusions of most previous workers, who have preferred an interpretation involving oscillatory or multidirectional flows (see previous section). Swift *et al.* (1983) support their conceptual reasoning with a description of 'hummocky megaripples' from the U.S. Atlantic Shelf. They suggest that these bedforms are equivalent to ancient examples of hummocky cross-stratification. Their evidence consists of three side-scan sonar records and two box cores. Tracings from their box cores (Swift *et al.*, 1983, fig. 5) are reproduced in Fig. 7. Swift *et al.* (1983) do not report dip angles of cross-stratification from these cores; however, the tracings may be used to determine the *apparent* dip of cross-strata. (Note that apparent

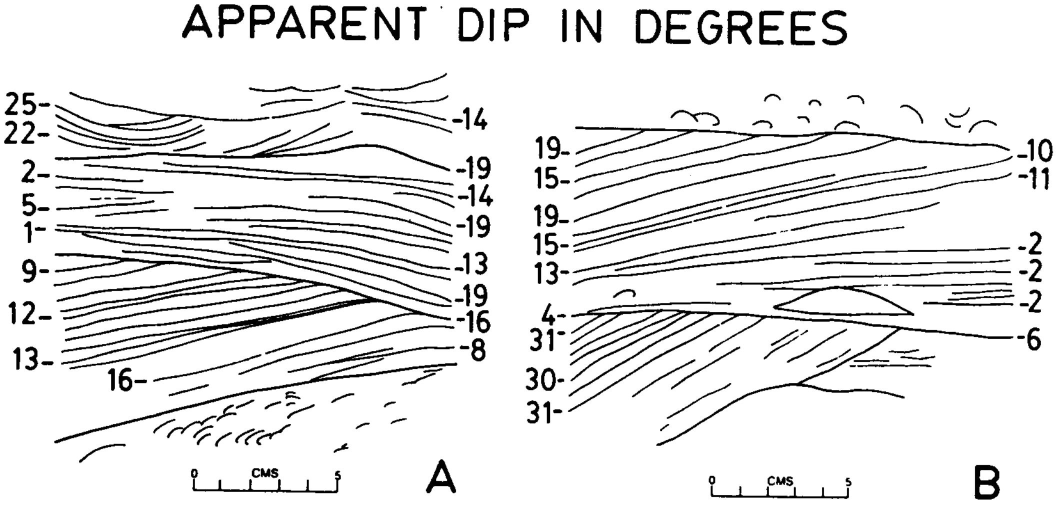


Fig. 7. Tracings of laminae from two box cores collected from the U.S. Atlantic shelf (after Swift *et al.*, 1983) showing measured values of *apparent dip* of cross-strata. Compare this high-angle cross-stratification to the low-angle cross-stratification in the hummocky sandstones of Fig. 1.

dip values may be equal to or less than true cross-stratification dip.) Figure 7 shows the measured values of apparent dip from these tracings; it it seen that these values attain a maximum of 31°, approximately the angle of repose of sand and greatly in excess of the typical dip values attained within hummocky cross-stratification. For the most part, the lower apparent dip values from these cores equal or exceed the maximum dip commonly attained within hummocky sandstones (approximately 10°–15°). I suggest that these relatively lower-angle cosets represent oblique views of cross-strata which also are near the angle of repose, and that these box cores probably have penetrated trough cross-bedding, not hummocky cross-stratification as suggested by Swift *et al.* (1983). These trough cross-beds may have been somewhat modified by storm waves (see below), but the cross-strata dip is far too great to represent true hummocky cross-stratification. In support of this interpretation, the laminae in the tracings generally thin into the trough, whereas in hummocky cross-stratification, laminae generally thicken into swales.

The three sonar records (Swift *et al.*, 1983, figs 3A, 4A, B) reveal a three-dimensional pattern of crests and troughs, a common feature of dunes formed by unidirectional currents. The generally flattened peaks apparent in portions of these records may indicate storm-wave reworking of the tops of these dunes. Note that Swift *et al.* (1983, p. 1296) state that for several years they thought 'the rather blurry bedforms that we saw on side-scan sonar were . . . merely so many wave-damaged and therefore substandard megaripples'. The evidence which they present suggests that this is indeed the case with these bedforms; they probably do not represent modern examples of hummocky cross-stratification. As suggested above, this interpretation is consistent with the observation that mid-latitude storms such as those described by Swift *et al.* (1983) typically generate unidirectional-dominant bottom flows, which would be expected to produce bedforms similar to those formed under purely unidirectional flow.

Because of the considerable doubt surrounding the true nature of these bedforms, I have designated this occurrence with a question mark in Table 3.

EXAMPLES OF HUMMOCKY CROSS-STRATIFICATION FROM NON-GLACIAL CLIMATES

Data presented above have established that an origin involving storm effects is consistent with the palaeogeographic distribution of hummocky cross-stratification deposited during times when the Earth's climate was essentially similar to that of today. Further, the distribution of these examples strongly suggests formation by both hurricanes and intense winter storms. In the following sections of this paper I *assume* that Mesozoic and Palaeogene occurrences of the structure were also formed by storms, and I examine the palaeogeographic settings in which the structure occurs in an attempt to determine the nature of major storms during times of non-glacial climate.

The distribution of major storms during the non-glacial Mesozoic and Palaeogene

In order to estimate the hurricane frequency distribution during non-glacial times, consider the major controls of hurricane initiation and development. Heat released from condensation of warm ocean-surface water vapour supplies energy to these storms, and the Coriolis effect forms their wind-intensifying spiral structure. While initiation of these cyclones is confined to low latitudes and dependent upon many variables (Gray, 1968), over geologic time the dominant controls of their frequency by latitude should be these two factors.

The decrease in modern hurricane frequency in the warmer latitudes lower than 20° probably results from a decrease in the magnitude of the Coriolis effect toward the equator. In high latitudes, where Coriolis effect is strong, the latent heat needed to drive hurricanes decreases poleward, as does the frequency of modern hurricanes. The poleward decrease in hurricane frequency must be in large part temperature controlled, as is suggested by the known relationship between hurricane frequency and intensity and the temperature of the underlying sea surface (Carlson, 1969b, 1971; Namias, 1969; Brand, 1971). In past times when mean ocean surface-water temperatures in higher latitudes were significantly warmer, hurricanes would have occurred at higher latitudes than they now do. Priestley (1966, see also Schopf, 1980, pp. 114–116) has argued that 33°C may have always been the maximum water temperature in the open ocean, but during warmer times (non-glacial) the poleward gradient of ocean surface-water temperature would have been much less steep.

From this brief analysis I infer that hurricanes may have ranged into higher latitudes during the much warmer Mesozoic and Palaeogene. Consistent with this is the suggestion of Adam (1975) that hurricanes act as a negative feedback mechanism to restrain high ocean-surface water temperatures (i.e. an increase in ocean-surface temperature causes an increase in the frequency and severity of hurricanes, which in turn act to dissipate heat from the surface waters of the ocean).

Now consider the factors which govern the initiation and development of intense winter storms. These cyclones form along fronts between cold polar and warm tropical air masses. Could such cold polar air masses have formed in the non-glacial winter, when extensive polar sea and land ice did not exist? Frakes (1979, p. 177) infers that extensive polar land areas were snow-covered in the winter during at least parts of the Mesozoic, suggesting that formation of cold polar air masses continued on the non-glacial earth (during winter only). It is impossible to directly estimate either the severity (areal extent and temperature) or the palaeolatitudinal distribution of these relatively colder polar air masses, nor is it possible accurately to evaluate the manner in which they interacted with the warmer tropical air masses formed during non-glacial times. I conclude that winter storms probably formed during these times, but it is impossible to directly estimate their strength and latitudinal zonation. Criteria for the recognition of hummocky cross-stratification formed by intense winter storms (developed below) may be used to evaluate tentatively the strength and zonation of winter disturbances during non-glacial times.

Mesozoic and Palaeogene examples of hummocky cross-stratification: discussion

The Mesozoic and Palaeogene examples are concentrated in higher latitudes than the older examples (Fig. 2B). It should be emphasized, however, that the small sample size ($n=33$) and the probable over-representation of the extensively studied Western Interior of North America most likely bias the distribution toward the middle latitudes. Some credibility derives from the consistency of the eight European, New Zealand, and Japanese examples; nevertheless, these results must be considered preliminary pending more extensive sampling from low and high palaeolatitudes.

In an attempt to identify the storms inferred to have produced hummocky cross-stratification in the Western Interior, a single criterion has been examined: shoreline configuration near the deposition site. Thus, units with a western or northern shoreline bordering the southern arm of the Western Interior epicontinental sea are assumed to have been hurricane influenced (see Fig. 8A). Examples having a southern shoreline bordering the northern extension of the Seaway are assumed to have been influenced by intense winter storms (see Fig. 8B). This distinction is supported in some cases by fossil evidence: e.g. the Moosebar-Gates, an inferred winter-storm occurrence, contains a boreal fauna (D. A. Leckie, 1981, pers. comm.), whereas the inferred hurricane-influenced Dunvegan

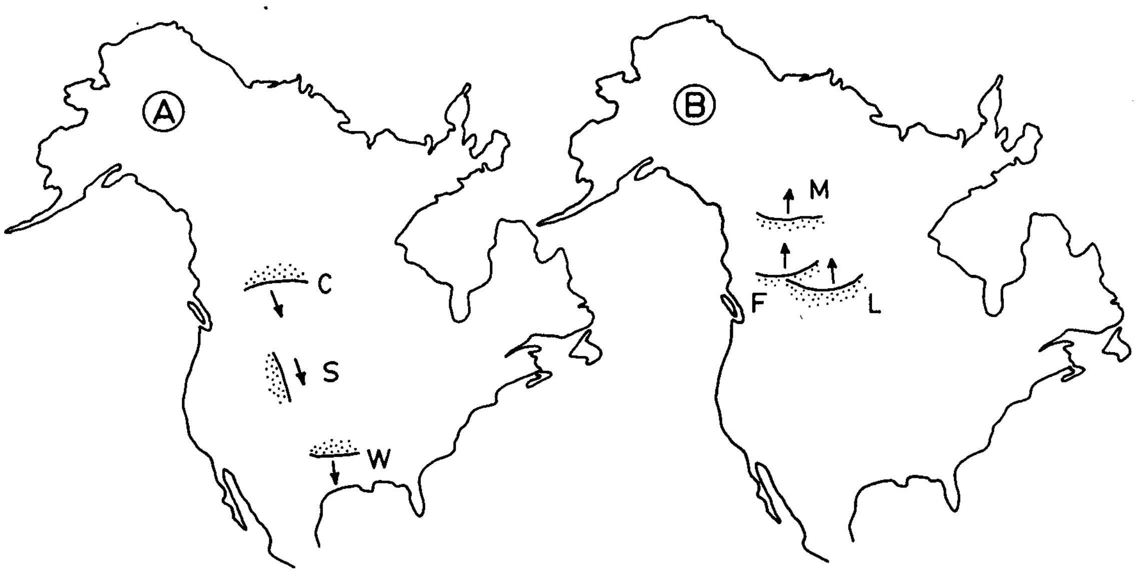


Fig. 8. Palaeogeography of selected Western Interior rock units displaying abundant hummocky cross-stratification. Group A examples have northern or western shorelines and are inferred hurricane deposits. Group B examples have southern shorelines and are inferred deposits of intense winter storms. Arrows indicate inferred palaeoflow directions. C = Cardium; S = Shannon, Sussex; W = Washita; M = Moosebar-Gates; F = Fernie-Kootenay; L = Mannville.

Formation contains a subtropical to warm-temperate flora (Stott, 1963, p. 144). It should be noted that the shoreline criterion described above may well allow the classification of some winter-storm deposits as hurricane deposits; however, this criterion has the advantage of identifying those deposits which definitely could *not* have been influenced by hurricanes.

The examples from the U.S. west coast are from geographical settings consistent with generation by intense winter storms; however, no attempt has been made to evaluate displacements due to subduction or strike-slip motions. Such displacements have offset these examples northward and/or eastward from their original site of deposition; therefore, these examples may have originated within the eastern North Pacific hurricane zone. Also, it is likely that this zone was more extensive in times when the climate was warmer and a Central American barrier did not exist, opening the Pacific to frequent invasion by Atlantic hurricanes. Such a connection between oceans is indicated from Late Jurassic to Eocene times in the reconstructions of Smith & Briden (1977). The west coast examples, therefore, cannot be classified by storm type. The European examples, open to the Tethys, were well situated to encounter strong hurricane effects, as were the New Zealand and Japanese examples.

The distribution of hummocky cross-stratification from non-glacial times (Fig. 2B) reflects the possibility of a broadened hurricane belt predicted by the preceding palaeoclimatological analysis. A belt of deposits which could not have been directly influenced by hurricanes is also recognized; it is more likely that these occurrences were influenced by intense winter storms. The inferred belt of winter-storm deposits occupies palaeolatitudes similar to the latitudes in which these storms occur in the modern world.

LACUSTRINE HUMMOCKY CROSS-STRATIFICATION: DISCUSSION

The deltaic deposits of Late Pleistocene Lake Bonneville have been examined in North Utah by Robert Q. Oaks, Jr (1982, pers. comm.). His description of lacustrine hummocky cross-stratification generated in water depths of 1–2 m is essentially identical to that of the various marine occurrences and suggests a similar process of formation. Oaks has inferred an origin involving storm processes. Because both hurricanes and intense winter storms forming over the sea surface are eliminated as possible generative agents, the storms that formed hummocky cross-stratification in Lake Bonneville were probably characterized by maximum wind velocities of less than hurricane force.

The palaeogeographic setting of these deposits is fully consistent with formation by less violent terrestrial wave cyclones (the 'Colorado cyclones', Petterssen, 19[illegible], p. 229). This example suggests that hummocky cross-stratification may be generated by storm effects of much less magnitude than those associated with the Earth's most intense weather disturbances. Lake Bonneville deposits are unique in that they contain a thick sequence (about 1 m) of hummocky cross-stratification; however, the structure is also known from two lacustrine units in Australia (R. G. Walker, 1982, pers. comm.). These units are the Triassic Narrabeen Formation (near Sydney, N.S.W.) and the Permian Tomago Formation (near Newcastle, N.S.W.). These Australian lacustrine units contain only two or three thin hummocky beds each; these beds may represent unusual conditions carrying no palaeolatitudinal significance. Thus, these units are not listed in Tables 1 and 2. Their palaeolatitudinal positioning, however, is fully consistent with generation by terrestrial wave cyclones. (Permian unit at 60°S, Triassic unit at 58°S.)

The preservation of lacustrine hummocky cross-stratification generated in very shallow water by minor storms does not imply that hummocky cross-stratification generated in shallow marine settings by minor storms will also be preserved. The greater severity of oceanic fair-weather waves, the presence of tidal currents, etc., greatly reduce the potential for preservation of storm-generated structures in very shallow marine settings. The shallow-marine record, therefore, may not contain hummocky cross-stratification formed by minor storms such as those which generated the structure in Lake Bonneville. For a further discussion of the palaeohydraulic significance of the Lake Bonneville example, see Duke (1984).

SUMMARY

The palaeolatitudinal and palaeogeographic distributions of 107 occurrences of hummocky cross-stratification have been examined. Such distributions cannot unequivocally demonstrate a genetic link between a sedimentary structure and a hypothetical generative agent; however, these distributions can be used to evaluate the likelihood of such a link. Bearing in mind this disclaimer of certitude, the principal results of this study are:

(1) All known examples of hummocky cross-stratification may be genetically attributed to direct storm effects. Most examples (73%) were formed by tropical hurricanes; the remainder were formed by intense mid-latitude winter storms.

(2) Examples of hummocky cross-stratification from pre-Mesozoic, Neogene, and Quaternary units (times of global climate similar to that of today) were generated both by hurricanes and intense winter storms. Most of these occurrences (69%) were formed by hurricanes. The latitudinal belts occupied by hurricanes and intense winter storms during these times were essentially identical to those occupied by their modern counterparts.

(3) Examples of hummocky cross-stratification from Mesozoic and Palaeogene units (times of non-glacial global climate) were also generated both by hurricanes and intense winter storms. Most of these occurrences (79%) were formed by hurricanes; their distribution suggests that a broadened hurricane belt existed during these much warmer times. The existence of a broadened hurricane belt during warmer times is consistent with climatological considerations, which indicate a less steep poleward gradient of ocean surface-water temperature on the non-glacial Earth. Furthermore, intense winter storms continued to form hummocky cross-stratification in the middle latitudes (at least in the northern hemisphere). The formation of intense winter storms during non-glacial times indicates formation of relatively cold polar air masses during winter (at least in the northern hemisphere). These cold polar air masses probably formed over extensive polar land areas covered with snow during the non-glacial winter.

(4) It is suggested herein that hurricanes are more efficient generators of hummocky cross-stratification because these storms couple less effectively with the water column than do intense winter storms. Due to this ineffective coupling, hurricane-generated surface gravity waves form powerful oscillatory or multidirectional flows at the sediment–water interface which do not possess a significant unidirectional component. In contrast, intense winter storms do couple effectively with the water column and thereby generate strong unidirectional flows at the bottom; these unidirectional currents overwhelm wave-generated oscillatory or multidirectional flows and inhibit formation of hummocky cross-stratification.

(5) Tsunamis very probably are not significant generative agents for hummocky cross-stratification.

(6) Hummocky cross-stratification from three lacustrine deposits indicates that terrestrial wave cyclones may strongly affect the sedimentary record of some large lakes.

The preceding conclusions differ essentially from those presented by Marsaglia & Klein (1983) and Swift *et al.* (1983). Both of these studies suggested that intense winter storms are more effective generators of hummocky cross-stratification than are hurricanes, a conclusion which is not supported by the palaeogeographic distribution of the structure. Further, Marsaglia & Klein (1983) suggested that three examples of hummocky cross-stratification were deposited in palaeogeographic settings which eliminate the possibility of a direct storm influence. Careful examination of the palaeogeographic settings of these and all other examples indicates that all occurrences of the structure may be attributed to direct storm effects associated with the passage of a major storm over the site of deposition.

As more examples of hummocky cross-stratification are recognized and the paucity of data is eliminated, more reliable palaeolatitudinal distributions of the structure will prove useful in discriminating between various hypothetical generative agents.

ACKNOWLEDGMENTS

This paper is an outgrowth from a preliminary manuscript prepared by the author in 1979. The final text has benefitted enormously from the comments of R. G. Walker, G. V. Middleton, D. J. P. Swift, R. H. Dott (Jr), P. H. Bridges, R. D. Kreisa, D. A. Leckie, R. J. Cheel, L. R. P. Rosenthal, T. Aigner, and several others. I am grateful to J. B. Southard, who introduced me to hummocky cross-stratification in 1976, and to M. A. Matteliano for her translation of the Italian paper. I am indebted to R. Q. Oaks (Jr), for permission to publish his observations from Lake Bonneville deposits, and I extend my gratitude to the many others whose helpful communications have enlarged the scope of this review. Special thanks go to Roger Walker for his patient encouragement of this research, which was supported by the Natural Science and Engineering Research Council of Canada (operating grant to R. G. Walker). The N.S.E.R.C. and Amoco Canada funded field work in Canada; work in the U.S.A. was supported by grants from the Research Fund of the American Association of Petroleum Geologists Foundation, McMaster University, and the Massachusetts Institute of Technology. This support is gratefully acknowledged. Finally, I would like to thank in advance any readers who may bring to my attention additional examples of hummocky cross-stratification.

REFERENCES

ADAM, D.P. (1975) The tropical cyclone as a global climatic stabilizing mechanism. *Geology*, **3**, 625–626.

AIGNER, T. (1982) Calcareous tempestites: storm dominated stratification in Upper Muschelkalk limestones (Middle Trias, S.W.-Germany). In: *Cyclic and Event Stratification* (Ed. by G. Einsele and A. Seilacher), pp. 180–198. Springer-Verlag, New York.

AIGNER, T. & REINECK, H.E. (1982) Proximality trends in modern storm sands from the Helgoland Bight (North Sea) and their implications for basin analysis. *Senckenberg. Mar.* **14**, 183–215.

ANDERTON, R. (1976) Tidal-shelf sedimentation: an example from the Scottish Dalradian. *Sedimentology*, **23**, 429–458.

ARNOLD, J.E. (1966) Easterly wave activity over Africa and in the Atlantic with a note on the intertropical convergence zone during early July 1961. *Satellite Mesomet. Res. Proj. Pap. No. 65*, Department of Geophysical Sciences, University of Chicago.

BALDWIN, C.T. & JOHNSON, H.D. (1977) Sandstone mounds and associated facies sequences in some late Precambrian and Cambro-Ordovician inshore tidal flat/lagoonal deposits. *Sedimentology*, **24**, 801–818.

BALL, M.M., SHIN, E.A. & STOCKMAN, K.W. (1967) The geologic effects of Hurricane Donna in south Florida. *J. Geol.* **75**, 583–597.

BANKS, N.L. (1973a) Innerelv Member: Late Precambrian marine shelf deposit, East Finnmark. *Norg. geol. Unders.* **288**, 7–25.

BANKS, N.L. (1973b) Tide-dominated offshore sedimentation, Lower Cambrian, north Norway. *Sedimentology*, **20**, 213–228.

BERG, R.R. (1975) Depositional environment of Upper Cretaceous Sussex sandstone, House Creek field, Wyoming. *Bull. Am. Ass. Petrol. Geol.* **59**, 2099–2110.

BERNARD, H.A., LEBLANC, R.J. & MAJOR, C.F. (1962) Recent and Pleistocene geology of southeast Texas, In: *Geology of Gulf Coast and Central Texas Guidebook*, pp. 175–224. Houston Geological Society, Houston.

BLOOSE, G. (1982) Shell beds in the Lower Lias of south Germany—facies and origin. In: *Cyclic and Event Stratification* (Ed. by G. Einsele, and A. Seilacher), pp. 223–239. Springer-Verlag, New York.

BOURGEOIS, J. (1980) A transgressive shelf sequence exhibiting hummocky stratification: the Cape Sebastian sandstone (Upper Cretaceous), southwestern Oregon. *J. sedim. Petrol.* **50**, 681–702.

BOYLES, J.M. & SCOTT, A.J. (1982a) Comparison of wave-dominated deltaic deposits and associated sand-rich strand plains, Mesaverde Group, north-west Colorado (abs). *Bull. Am. Ass. Petrol. Geol.* **66**, 551–552.

BOYLES, J.M. & SCOTT, A.J. (1982b) A model for migrating shelf-bar sandstones in upper Mancos Shale (Campanian), northwestern Colorado. *Bull. Am. Ass. Petrol. Geol.* **66**, 491–508.

BRAND, S. (1971) The effects on a tropical cyclone of cooler surface waters due to upwelling and mixing produced by a prior tropical cyclone. *J. appl. Met.* **10**, 865–874.

Brenchley, P.J., Newall, G. & Stanistreet, I.G. (1979) A storm surge origin for sandstone beds in an epicontinental platform sequence, Ordovician, Norway. *Sedim. Geol.* **22**, 185–217.

Brenner, R.L. (1978) Sussex sandstone of Wyoming—example of Cretaceous offshore sedimentation. *Bull. Am. Ass. Petrol. Geol.* **62**, 181–200.

Brett, C.E. (1982) Stratigraphy and facies variation of the Rochester Shale (Silurian: Clinton Group) along Niagara Gorge. In: *Guidebook for Field Trips in Western New York, Northern Pennsylvania and Adjacent, Southern Ontario* (Ed. by E. J. Buehler and P. E. Calkin), pp. 217–246. New York State Geological Association.

Bridges, P.H. (1972) The significance of toolmarks on a Silurian erosional furrow. *Geol. Mag.* **109**, 405–410.

Bridges, P.H. (1975) The transgression of a hard substrate shelf: the Llandovery (Lower Silurian) of the Welsh Borderland. *J. sedim. Petrol.* **45**, 79–94.

Boekman, J.A. (1973) Sedimentary structures and palaeoecology of the Pliocene Kritika Formation in a section near Kalithies (Rhodos, Greece). *Proc. K. ned. Akad. Wet., Ser. B*, **76**, 423–445.

Buller, A.T. & Johnsen, S.O. (1982) Storm-influenced marine sandstones in the Ordovician Lower Hovin Group, Nord-Trøbdekag. *Norsk geol. Tidsskr.* **62**, 211–217.

Campbell, C.V. (1966) Truncated wave-ripple laminae. *J. sedim. Petrol.* **36**, 825–828.

Campbell, C.V. (1971) Depositional model—Upper Cretaceous Gallup beach shoreline, Ship Rock area, northwestern New Mexico. *J. sedim. Petrol.* **41**, 395–409.

Campbell, C.V. & Oaks, R.Q. (Jr) (1973) Estuarine sandstone filling tidal scours, Lower Cretaceous Fall River Formation, Wyoming. *J. sedim. Petrol.* **43**, 765–778.

Cant, D.J. (1980) Storm-dominated shallow marine sediments of the Arisaig Group (Silurian-Devonian) of Nova Scotia. *Can. J. Earth Sci.* **17**, 120–131.

Carlson, T.N. (1969a) Synoptic histories of three African disturbances that developed into Atlantic hurricanes. *Mon. Weath. Rev.* **97**, 256–276.

Carlson, T.N. (1969b) Some remarks on African disturbances and their progress over the tropical Atlantic. *Mon. Weath. Rev.* **97**, 716–726.

Carlson, T.N. (1971) An apparent relationship between the sea-surface temperature of the tropical Atlantic and the development of African disturbances into tropical storms. *Mon. Weath. Rev.* **99**, 309–310.

Carstens, M.R., Neilson, F.M. & Altinbilek, H.D. (1969) Bed forms generated in the laboratory under oscillatory flow: analytical and experimental study. *U.S. Army Corps Engrs, Coastal Eng. Res. Cent., Tech. Memo. 28.*

Conrad, K.T. & Oaks, R.Q. (Jr) (1982) Arumbera Sandstone: a possible Late Proterozoic-Early Cambrian deltaic complex, central Australia (abs.). *Bull. Am. Ass. Petrol. Geol.* **66**, 559.

Cotter, E. (1975) Late Cretaceous sedimentation in a low-energy coastal zone: the Ferron Sandstone of Utah. *J. sedim. Petrol.* **45**, 669–685.

Della Favera, J.C. (1982) Devonian storm- and tide-dominated shelf deposits, Parnaiba basin, Brazil (abs.). *Bull. Am. Ass. Petrol. Geol.* **66**, 562.

De Raaf, J.F.M., Boersma, J.R. & Van Gelder, A. (1977) Wave-generated structures and sequences from a shallow marine succession, Lower Carboniferous, County Cork, Ireland. *Sedimentology*, **24**, 451–483.

Dott, R.H. (Jr) (1974) Cambrian tropical storm waves in Wisconsin. *Geology*, **2**, 243–246.

Dott, R.H. (Jr) & Bird, K.J. (1979) Sand transport through channels across an Eocene shelf and slope in southwestern Oregon, U.S.A. In: *Geology of Continental Slopes* (Ed. by L. J. Doyle & O. H. Pilkey). *Spec. Publ. Soc. econ. Paleont. Mineral. Tulsa*, **27**, 327–342.

Dott, R.H. (Jr) & Bourgeois, J. (1982) Hummocky stratification: significance of its variable bedding sequences. *Bull. geol. Soc. Am.* **93**, 663–680.

Duke, W.L. (1980) Upper Cretaceous (Turonian) Cardium Formation, Southern Alberta. *Tech. Mem.* 80–4 *Dept Geol., McMaster Univ.*, 59 pp.

Duke, W.L. (1981) Internal stratigraphy and palaeogeography of the Upper Cretaceous Cardium Formation in the Alberta Foothills (abs.). *Abstr. geol. Ass. Can.* **6**, A-38.

Duke, W.L. (1982a) Hummocky cross-stratification, tropical hurricanes, and intense winter storms (abs.). *Abstr. Prog. geol. Soc. Am.* **14**, 478.

Duke, W.L. (1982b) The 'type locality' of hummocky cross-stratification: the storm-dominated Silurian Medina Formation in the Niagara Gorge, New York and Ontario. *Proc. Ont. Petrol. Inst.* **21**, 2.1–2.31.

Duke, W.L. (1984) Paleohydraulic analysis of hummocky cross-stratified sands indicates equivalence with wave-formed flat bed: Pleistocene Lake Bonneville deposits, northern Utah (abs.). *Bull. Am. Ass. Petrol. Geol.* **68**, 472.

Duke, W.L., Ainsworth, B.H. & Walker, R.G. (1980) Storm-dominated coarsening-upward clastic sequences in the Cardium Formation, Upper Cretaceous, Southern Alberta (abs.). *Abstr. geol. Soc. Am. Prog.* **12**, 32.

Duke, W.L. & Leckie, D.A. (1984) Origin of hummocky cross-stratification. Part 2. Paleohydraulic analysis indicates formation by orbital ripples within the wave-formed flat-bed field (abs.). *Can. Soc. Petrol. Geol., Shelf Sands and Sandstones Symp.* Program and Abstracts, p. 32.

Fairchild, H.L. (1901) Beach structure in Medina sandstone. *Am. Geol.* **28**, 9–14.

Frakes, L.A. (1979) *Climates throughout Geologic Time.* Amsterdam, Elsevier.

Ghibaudo, G., Mutti, E. & Rosell, J. (1974) Le spiagge fossili delle arenarie di Aren (Cretacico Superiore) nella Valle Noguera Ribagorzana (Pirenei Centro-Meridionali, Province di Lerida e Huesca, Spagna). *Memorie Soc. geol. ital.* **13**, 497–537.

Gilbert, G.K. (1899) Ripple-marks and cross-bedding. *Bull. geol. Soc. Am.* **10**, 135–140.

Goldring, R. (1971) Shallow-water sedimentation as illustrated in the Upper Devonian Baggy Beds. *Mem. geol. Soc. London, No. 5*, 80 pp.

Goldring, R. & Bridges, P. (1973) Sublittoral sheet sandstones. *J. sedim. Petrol.* **43**, 736–747.

Goldring, R. & Stephenson, D.G. (1972) The depositional environment of three Starfish Beds. *Neues Jb. Geol. Paleont. Mh.*, **10**, 611–624.

Graham, J.R. (1982) Transition from basin-plain to shelf deposits in the Carboniferous flysch of southern Morrocco. *Sedim. Geol.* **33**, 173–194.

Gray, W.M. (1968) Global view of the origin of tropical disturbances and storms. *Mon. Weath. Rev.* **96**, 669–700.

Hamblin, A.P., Duke, W.L. & Walker, R.G. (1979) Hummocky cross-stratification—indicator of storm-dominated shallow-marine environment (abs.). *Bull. Am. Ass. Petrol. Geol.* **63**, 460–461.

Hamblin, A.P. & Walker, R.G. (1979) Storm-dominated shallow marine deposits: the Fernie-Kootenay (Jurassic) transition, southern Rocky Mountains. *Can. J. Earth Sci.* **16**, 1673–1690.

Harms, J.C., MacKenzie, D.B. & McCubbin, D.G. (1965) Depositional environment of the Fox Hills Sandstone near Rock Springs, Wyoming. *Rocky Mtn. Ass. Geologists 19th Field Conf. Gdbk*, pp. 113–130.

Harms, J.C., Southard, J.B., Spearing, D.R. & Walker, R.G. (1975) Depositional environments as interpreted from primary sedimentary structures and stratification sequences. *Soc. econ. Paleont. Mineral., Tulsa, Short Course No. 2*, 161 pp.

Harms, J.C., Southard, J.B. & Walker, R.G. (1982) Structures and sequences in clastic rocks. *Soc. econ. Paleont. Mineral., Tulsa, Short Course No. 9*.

Hayes, M.O. (1967) Hurricanes as geological agents: case studies of hurricanes Carla 1961, and Cindy, 1963. *Texas Bur. econ. Geol. Rep. Invest. No. 61*, 54 pp.

Hein, F.J. (1982) Facies associations in slope-to-shelf transition: Precambrian Miette to Lower Cambrian Gog Group, Kicking Horse Pass, southern Canadian Rocky Mountains (abs.). *Bull. Am. Ass. Petrol. Geol.* **66**, 580.

Hobday, D.K. & Morton, R.A. (1980) Lower Cretaceous shelf storm deposits, north Texas (abs.). *Bull. Am. Ass. Petrol. Geol.* **64**, 723.

Howard, J.D. (1972) Trace fossils as criteria for recognizing shorelines in the stratigraphic record. In: *Recognition of Ancient Sedimentary Environments* (Ed. by J. K. Rigby and W. K. Hamblin). *Spec. Publ. Soc. econ. Paleont. Mineral., Tulsa, No. 16*, 215–225.

Howard, J.D. & Reineck, H.-E. (1972) Physical and biogenic sedimentary structures of the nearshore shelf: in Georgia coastal region, Sapelo Island, U.S.A.: sedimentology and biology. *Senckenberg. Mar.* **4**, 81–123.

Howard, J.D. & Reineck, H.-E. (1979) Sedimentary structures of a 'high-energy' beach-to-offshore sequence, Ventura-Port Hueneme area, California (abs.). *Bull. Am. Ass. Petrol. Geol.* **63**, 468–469.

Howard, J.D., Kamola, D. & Salazar, A. (1982) Depositional facies of Cretaceous Spring Canyon Member, Blackhawk Formation, Book Cliffs, Utah (abs.). *Bull. Am. Ass. Petrol. Geol.* **66**, 584.

Hunter, R.E. & Clifton, H.E. (1982) Cyclic deposits and hummocky cross-stratification of probable storm origin in Upper Cretaceous rocks of the Cape Sebastian area, Southwestern Oregon. *J. sedim. Petrol.* **52**, 127–143.

Hurst, J.M. (1979) The environment of deposition of the Caradoc Alternata Limestone and contiguous deposits of Salop. *Geol. J.* **14**, 15–40.

Hurst, J.M. & Hewitt, R.A. (1977) On Tubular problematica from the type Caradoc (Ordovician) of England. *Neues Jb. Geol. Paläont. Abh.*, **153**, 147–169.

Johnson, H.D. (1977) Shallow marine sand bar sequences: an example from the late Precambrian of North Norway. *Sedimentology*, **24**, 245–270.

Kaldi, J.G. (1980) *Aspects of the sedimentology of the Lower Magnesian Limestone (Permian) of Eastern England.* Unpublished Ph.D. thesis, University of Cambridge.

Katto, J. & Taira, A. (1978) The Misaki Group (Miocene), southwestern Shikoku. *Kochi Univ. Res. Rep.* **27**, 165–180.

Kazmierczak, J. & Goldring, R. (1978) Subtidal flat-pebble conglomerate from the Upper Devonian of Poland: a multiprovenent high-energy product. *Geol. Mag.* **115**, 359–366.

Kelling, G. & Mullin, P.R. (1975) Graded limestones and limestone-quartzite couplets: possible storm-deposits from the Moroccan Carboniferous. *Sedim. Geol.* **13**, 161–190.

Kreisa, R.D. (1981) Storm-generated sedimentary structures in subtidal marine facies with examples from the Middle and Upper Ordovician of southwestern Virginia. *J. sedim. Petrol.* **51**, 823–848.

Landsberg, H.E. (1960) Do tropical storms play a role in the water balance of the northern hemisphere? *J. geophys. Res.* **65**, 1305–1307.

Leckie, D.A. & Duke, W.L. (1984) Origin of hummocky cross-stratification. Part 1. Straight-crested symmetrical gravel dunes—the coarse-grained equivalent of hummocky cross-stratification (abs.). *Can. Soc. Petrol. Geol., Shelf Sands and Sandstones Symp.* Program and Abstracts, p. 51.

Leckie, D.A. & Walker, R.G. (1982) Storm- and tide-dominated shorelines in Cretaceous Moosebar-Lower Gates interval—outcrop equivalents of Deep basin gas trap in western Canada. *Bull. Am. Ass. Petrol. Geol.* **66**, 138–157.

Lerand, M.M. (1982) Chungo (Sandstone) Member, Wapiabi Formation at Mt Yamnuska, Alberta. In: *IAS Field Excursion Guide Book 21A: Clastic Units of the Front Ranges, Foothills and Plains in the Area between Field, B.C., and Drumheller, Alberta* (Ed. by R. G. Walker), pp. 96–116. International Association of Sedimentologists.

Lewis, D.W. (1980) Storm-generated graded beds and debris flow deposits with *Ophiomorpha* in a shallow offshore Oligocene sequence at Nelson, South Island, New Zealand. *N.Z. J. Geol. Geophys.* **23**, 353–369.

Lofquist, K.E.B. (1978) Sand ripple growth in an oscillatory-flow water tunnel. *U.S. Army Corps Engrs, Coastal Eng. Res. Cent., Tech. Pap. 78-5*.

Lorsong, J.A. (1982) Channels and chimeras: coastal vs. fluvial deposition of Mannville Group, Lloydminster area, Saskatchewan (abs.). *Bull. Am. Ass. Petrol. Geol.* **66**, 596.

Markello, J.R. & Read, J.F. (1981) Carbonate ramp-to-deeper shale shelf transitions of an Upper Cambrian intrashelf basin, Nolichucky Formation, southwest Virginia Appalachians. *Sedimentology*, **28**, 573–597.

Marsaglia, K.M. & Klein, G. deV. (1983) The paleogeography of Paleozoic and Mesozoic storm depositional systems. *J. Geol.* **91**, 117–142.

Masuda, F., Katsura, Y., Sato, T., Aono, H., Makino, Y. & Igo, H. (1980) Shallow marine deposits of Triassic-Jurassic age in the Yamizo and Ashio Mountains, Northern Kanto, Japan. *Ann. Rep. Inst. Geosci. Univ. Tsukuba*, **6**, 62–69.

Masuda, F., Amano, K., Katsura, Y. & Ito, M. (1981) Shallow marine facies of Neogene and Quaternary strata at the northwest and southeast parts of Teshio Town in Hokkaido. *Human Culture and Environmental Studies in Northern Hokkaido*, **2**, 29 pp.

May, J.A. (1982) Progradational conglomeratic shoreline, Eocene of San Diago (abs.). *Bull. Am. Ass. Petrol. Geol.* **66**, 602.

Meijer Drees, N.C. & Mhyr, D.W. (1981) The Upper Cretaceous Milk River and Lea Park Formations in southeastern Alberta. *Bull. Can. Petrol. Geol.* **29**, 42–74.

Meyer, D.L., Tobin, R.C., Pryor, W.A., Harrison, W.B. & Osgood, R.C. (1981) Stratigraphy, sedimentology, and paleoecology of the Cincinnatian Series (Upper Ordovician) in the vicinity of Cincinnati, Ohio. In: *Geological Society of Am. 1981 Field Trip Gdbk* (Ed. by T. G. Roberts), **1**, 31–72.

Middleton, L.T., Steidtmann, J.R. & DeBoer, D.A. (1980) Stratigraphy and depositional setting of some Middle and Upper Cambrian rocks, Wyoming. *Wyoming geol. Ass. 32nd Ann. Guidebook*, pp. 23–35.

Mount, J.F. (1982) Storm-surge-ebb origin of hummocky cross-stratified units of the Andrews Mountain Member, Campito Formation (Lower Cambrian), White-Inyo Mountains, eastern California. *J. sedim. Petrol.* **52**, 941–958.

Namias, J. (1969) On the causes of the small number of Atlantic hurricanes in 1968. *Mon. Weath. Rev.* **97**, 346–348.

Oaks, R.Q. (Jr) & James, W.C. (1980) The Kinnikinic Quartzite (Middle Ordovician) in the type area, central Idaho, and a new reference section near Arco, Idaho: *Brigham Young Univ. geol. Stud.* **27**, 1–9.

Perkins, R.D. & Enos, P. (1968) Hurricane Betsy in the Florida–Bahama area—geologic effects and comparison with Hurricane Donna. *J. Geol.* **76**, 710–717.

Petterssen, S. (1958) *Introduction to Meteorology*. 2nd ed. McGraw-Hill, New York.

Priestley, C.H.B. (1966) The limitation of temperature by evaporation in hot climates. *Agric. Met.* **3**, 241–246.

Rahmani, R.A. (1982) Facies relationships and paleoenvironments of a tide-dominated delta—an estuarine-barrier complex in a mesotidal setting, Upper Cretaceous, Drumheller, Alberta (abs.). *Bull. Am. Ass. Petrol. Geol.* **66**, 621.

Rainone, M., Nanni, T. & Ori, G.G. (1981) A prograding gravel beach in Pleistocene fan delta deposits south of Ancona, Italy (abs.). *Abst. int. Ass. Sediment.* pp. 155–156. Second European Meeting, Bologna, Italy.

Ramaekers, P. (1979) Stratigraphy of the Athabasca Basin. In: *Summary of Investigations, 1979* (Ed. by J. E. Christopher and R. MacDonald), pp. 154–160. Saskatchewan Geological Survey.

Reineck, H.-E. & Singh, I.B. (1971) Der Golf von Gaeta (Tyrrenisches Meer). *Senckenberg. Mar.* **3**, 185–201.

Ricci Lucchi, F., Colella, A., Ori, G.G., Ogliani, F. & Colalongo, M.L. (1981) Pliocene fan deltas of the Intra-Apenninic Basin, Bologna. *Gdbk, Excursion No. 4, int. Ass. Sedimentol.* Second European Meeting, Bologna, Italy.

Rice, D.D. (1980) Coastal and deltaic sedimentation of Upper Cretaceous Eagle Sandstone: relation to shallow gas accumulations, north-central Montana. *Bull. Am. Ass. Petrol. Geol.* **64**, 316–338.

Riehl, H. (1965) *Introduction to the Atmosphere*. McGraw-Hill, New York.

Roep, Th. B., Beets, D.J., Dronkert, H. & Pagnier, H. (1979) A prograding coastal sequence of wave-built structures of Messinian age, Sorbas, Almeria, Spain. *Sedim. Geol.* **22**, 135–163.

Ross, G.M. (1982) The Narakay volcanic complex: mafic volcanism in the Helikian Hornby Bay Group of Dease Arm, Great Bear Lake: a preliminary report on depositional processes and tectonic significance. *Current Res., Part A, geol. Surv. Can. Pap. 82-1A*, 329–340.

Schopf, T.J.M. (1980) *Paleoceanography*. Cambridge, Massachusetts, Harvard University Press.

Scotese, C.R., Bambach, R.K., Banton, C., Van Der Voo, R. & Ziegler, A.M. (1979) Palaeozoic base maps. *J. Geol.* **87**, 217–277.

Sellwood, B.W. (1978) Biogenic sedimentary structures. In: *Encyclopedia of Sedimentology* (Ed. by R. W. Fairbridge and J. Bourgeois), pp. 61–64. Dowden, Hutchinson & Ross, Stroudsburg.

Smith, A.G. & Briden, J.C. (1977) *Mesozoic and Cenozoic Paleocontinental Maps*. Cambridge University Press.

Southard, J.B. (1984) Laboratory studies of oscillating-flow bed configurations and their bearing on stratification in shallow-marine sands (abs.). *Can. Soc. Petrol. Geol., Shelf Sands and Sandstones Symp.* Program and Abstracts, p. 65.

Spearing, D.R. (1976) Upper Cretaceous Shannon Sandstone: an offshore, shallow-marine sand body. *Wyoming geol. Ass. 28th Ann. Gdbk*, pp. 65–72.

Squires, R.L. (1981) A transitional alluvial to marine sequence: the Eocene Llajas Formation, southern California. *J. sedim. Petrol.* **51**, 923–938.

Stott, D.F. (1963) The Cretaceous Alberta Group and equivalent rocks, Rocky Mountain Foothills, Alberta. *Mem. geol. Surv. Can.* **317**, 306 pp.

Strahler, A.N. & Strahler, A.H. (1979) *Elements of Physical Geography*. 2nd ed. Wiley, New York.

Swift, D.J.P., Figueiredo, A.G. (Jr), Freeland, G.L. & Oertel, G.F. (1983) Hummocky cross-stratification and megaripples: a geological double standard? *J. sedim. Petrol.* **53**, 1295–1317.

Vos, R.G. (1977) Sedimentology of an Upper Paleozoic river, wave, and tide influenced delta system in Southern Morrocco. *J. sedim. Petrol.* **47**, 1242–1260.

Vos, R.G. & Hobday, D.K. (1977) Storm beach deposits in the Late Palaeozoic Ecca Group of South Africa. *Sedim. Geol.* **19**, 217–232.

Walker, R.G. (1979) Shallow marine sands. In: *Facies Models, Geosci. Canada, Reprint Ser. 1* (Ed. by R. G. Walker), pp. 75–89. Kitchener, Ontario, Ainsworth Press.

Walker, R.G., Duke, W.L. & Leckie, D.A. (1983) Hummocky stratification: significance of its variable bedding sequences: discussion. *Bull. geol. Soc. Am.* **94**, 1245–1249.

Walker, R.G., Hunter, D.F. & Bullock, A. (1981) Wapiabi–Belly River transition; storm-influenced sediments with north-oriented paleoflow, southern Alberta. *Abs. geol. Ass. Can.* **6**, A-59.

Wescott, W.A. (1982) Depositional setting and history of the Tar Springs Sandstone (Upper Mississippian), Southern Illinois. *J. sedim. Petrol.* **52**, 353–366.

Winn, R.D. (Jr), Stonecipher, S.A. & Bishop, M.G. (1983) Depositional environments and diagenesis of offshore sand ridges, Frontier Formation, Spearhead Ranch Field, Wyoming. *Mount. Geol.* **20**, 41–58.

Wright, M.E. & Walker, R.G. (1981) Cardium Formation (U. Cretaceous) at Seebe, Alberta—storm-transported sandstones and conglomerates in shallow marine depositional environments below fair-weather wave base. *Can. J. Earth Sci.* **18**, 795–809.

WU, X.T. (1982) Storm-generated depositional types and associated trace fossils in Lower Carboniferous shallow-marine carbonates of Three Cliffs Bay and Ogmore-by-Sea, South Wales. *Palaeogeogr. Palaeoclim. Palaeoecol.* **39**, 187–202.

(*Manuscript received 21 August 1983; revision received 14 August 1984*)

APPENDIX

Table 1. Proterozoic and Palaeozoic examples of hummocky cross-stratification

Rock unit, age, location	Palaeo-latitude[a]	Type of storm[b]	Criteria for H.C.S.[c]	Reference(s)
Hornby Bay Group Palaeohelikian to Late Hadrynian, Middle to Late Proterozoic Northwest Territories, Canada	n.a.[d]	n.a.	H	Ross (1982)
Athabasca Group Middle Helikian, Middle to Late Proterozoic North Saskatchewan	28°	HUR	H	Ramaekers (1979) P. Ramaekers (1982, pers. comm.)
Crystal Springs Formation Late Proterozoic SE California	n.a.	n.a.	H	This paper
Johnnie Formation Late Proterozoic SE California	n.a.	n.a.	H	This paper
Innerelv Member Late Proterozoic North Norway	n.a.	n.a.	I	Banks (1973a)
Dakkovarre Formation Late Proterozoic North Norway	n.a.	n.a.	I	Johnson (1977)
Stangenes Formation Late Riphean, Late Proterozoic North Norway	n.a.	n.a.	I	Baldwin & Johnson (1977)
Brachina Formation Adelaidean, Late Proterozoic N.S.W. Australia	n.a.	n.a.	H	Walker *et al.* (1983)
Jura Quartzite Dalradian, Late Proterozoic to Early Cambrian SW Scotland	28°S	HUR	I	Anderton (1976)
Arumbera Sandstone Late Proterozoic to Early Cambrian Central Australia	40°N	WIN	H	Conrad & Oaks (1982)
Campito Formation Early Cambrian California	10°N	HUR	H	Mount (1982)
Duolbasgaissa Formation Early Cambrian North Norway	11°S	HUR	I	Banks (1973b)

[a] Palaeolatitude (see text for sources).

[b] Type of storm effects encountered at site of deposition deduced from palaeogeographic setting:

HUR = susceptible to strong hurricane effects associated with passage of hurricanes directly over depositional site and/or landfall of hurricanes at nearby shoreline.

WIN = susceptible to strong storm effects associated with passage of intense winter storms directly over depositional site and/or landfall of intense winter storms at nearby shoreline.

[c] Types of criteria used to recognize hummocky cross-stratification (see text)

[d] Not available.