PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Palaeowind: Geological Criteria for Direction and Strength [and Discussion]

J. R. L. Allen and J. T. Parrish

Phil. Trans. R. Soc. Lond. B 1993 **341**, 235-242
doi: 10.1098/rstb.1993.0108

Palaeowind: geological criteria for direction and strength

J. R. L. ALLEN

Postgraduate Research Institute for Sedimentology, University of Reading, Reading RG6 2AB, U.K.

SUMMARY

The practical geological indicators of palaeowind are several scalar properties (bed thickness, grain size and sorting, mineral proportions) and directional structures (dune forms, yardangs and wind furrows, dune cross-bedding, windblown trees, wind ripples, adhesion ripples, flutes and grooves). These indicators ideally should be sampled so as to minimize geographical bias, and the data assessed so as to afford smoothed paths of sand and dust flow. Because most geological wind-related processes involve a threshold wind speed and proceed nonlinearly, inferred patterns of sand and dust flow may not exactly match patterns of the time-averaged wind direction. The use and potential of palaeowind indicators are well illustrated by windblown trees (mid Flandrian, southwest Britain) and by dune cross-bedding (Palaeozoic–Mesozoic, U.S.A.).

1. INTRODUCTION

The contemporary climate of a place on the Earth's surface is describable in terms of the instrumentally measured mean, range and pattern in time of temperature, precipitation, wind strength and wind direction (Chandler & Gregory 1973; McIlveen 1992). In principle, the climate of that place during some past epoch – its palaeoclimate – can also be framed in these terms, but the challenge of palaeoclimatology is to identify and exploit from rock sequences those features which carry with them a precise and unambiguous record of transient climatic conditions. Considerable progress remains to be made in the rigorous application of geological indicators to palaeoclimatic studies, not only globally but also at hemispheric and regional levels. Palaeowind studies, however, have so far taken a subordinate place to work on palaeotemperate and palaeoprecipitation, being restricted at the systematic level almost exclusively to arid areas (e.g. McKee 1979*a*; Peterson 1988). This paper seeks to redress the balance by reviewing the geological indicators of palaeowind, and by pointing to an indicator from non-arid areas, in the hope of encouraging their greater future use.

2. GEOLOGICAL INDICATORS OF PALAEOWIND

(*a*) *General*

A geological indicator of wind properties (Cooke & Warren 1973; Allen 1982; Greeley & Iversen 1985; Pye 1987; Pye & Tsoar 1990) can be an effective palaeoclimatic tool only if it is: (i) reasonably common; (ii) of high geological preservation potential; (iii) easily recognized and measured; and (iv) capable of unique or at least statistical interpretation. Relatively few geological features, divisible between scalar and directional (vector) types (Potter & Pettijohn 1977), prove usable.

(*b*) *Scalar indicators*

Spatial gradients of bed thickness, grain size (mean, extreme) and sorting, and mineral proportions, normally exhibiting a degree of correlation, are typical of sheets of sediment deposited downstream from sources from which particles can be dispersed by the wind. Models are available for the description of such dispersion (Hassan & Eltayeb 1991; Eltayeb & Hassan 1992).

The most important point sources are the more explosive types of volcano, which erupt ash intermittently for relatively very short periods at a time. Coarse debris spreads ballistically from their vents, but the finer particles, advected and diffused over a great range of height in the atmosphere, travel far in suspension in the turbulent wind before alighting within a generally elongated plume, which can attain a length of the order of 1000 km and a width of as much as 250 km (Allen 1982; Fisher & Schmincke 1984). Plume thickness and grain mean size tend to decline along the axis away from the source and at right-angles away from the axis. Systematic changes in the crystal–lithic–glass ratio may occur.

Rivers are important long-term, linear sources of sand and dust which can be transported by the wind over horizontal distances of many tens of kilometres, as illustrated by North American loess (e.g. Lugn 1968; Fehrenbacker *et al.* 1965; Snowden & Priddy

Phil. Trans. R. Soc. Lond. B (1993) **341,** 235–242
Printed in Great Britain

1968; Ruhe 1969; Handy 1976). These deposits thin with increasing distance from source, at first rapidly and then more gradually, and sands rarely spread further than several kilometres. The Pleistocene aeolian deposits of Belgium display a similar textural decline, from sands, through sandloess, to loess south of the westward-flowing Rhine (Pye & Tsoar 1990).

Large distributed sources of sand and particularly dust are provided by deserts, where rocks undergo weathering, and by dry alluvial plains (e.g. glacier outwash plains), to which debris is introduced from external sources (Pye 1987). Dust dispersed high into the atmosphere from these sources can travel for thousands of kilometres and reach the ocean (e.g. Rea & Leinen 1988; Pye & Zhou 1989), where it contributes to ocean-floor sediments, in which its relative abundance and grain size may vary substantially in time and space due to climate changes. Differential transport of the slower moving sand can also create regional textural gradients (e.g. Lancaster 1986).

(*c*) *Directional (vector) indicators*

Directional geological indicators of palaeowind, affording either its ground-level path or at least alignment, are more numerous and wider in origin than the scalar features. Their dimensions range from millimetres on the one hand to tens of kilometres at the other extreme.

Among the largest indicators are yardangs (Allen 1982; Greeley & Iversen 1985) and wind furrows (Mainguet 1972) which, because they are landforms – not restricted to Earth – due to natural sand-blasting (Allen 1982; Greeley & Iversen 1985), have a good chance of arising at unconformity surfaces (e.g. Allen 1982). Yardangs are streamlined, whaleback-shaped masses of rock or partly consolidated sediment aligned with the wind that measure a few to tens of metres in height and from tens to hundreds of metres in length. Typically, they taper downwind from a steep, blunt and, in some cases, overhanging end. Wind furrows commonly accompany yardangs. They are wind-aligned systems of broad rock ridges and valleys, many of the latter partly filled with chains of aeolian dunes, having a transverse spacing of the order of 1 kilometre. The Tibesti (Tchad) area is widely marked by furrows, their regional pattern revealing the deflection of the wind by the massif; Tewes & Loope (1992) describe fossil examples. Wind furrows denote only the alignment of the wind.

Aeolian sand dunes (Breed & Grow 1979; Fryberger 1979; Greeley & Iversen 1985; Pye & Tsoar 1990) – barkhan, transverse, longitudinal (seif), and star-dome – are large to very large constructional land forms of high preservation potential, the shape and orientation of which are a direct response to wind régime in deserts, periglacial regions, and exposed coasts. Recent climatic changes, especially those encouraging pedogenesis and revegetation, have led to the intermittent to permanent stabilization of many dune fields (e.g. Sarnthein 1978; Ahlbrandt *et al.* 1983; Goudie 1983; Lancaster 1992).

The internal cross-bedding structures of aeolian sand dunes, as recorded at outcrop in aeolian sandstones or from borehole dipmeter studies, are reflections of the shape and movement of the dunes, and perhaps the most important medium-scale indicators of palaeowind (Brookfield 1977; McKee 1979*b*; Rubin 1987). Four main bedding types can be present (Hunter 1977; Kocurek & Dott 1981). Sand-flow cross-strata are steep (*ca.* 25–35°) laminae formed as avalanches of dry sand drove down the steep, sheltered sides of dunes. The magnitude and azimuth of their dip denotes a local direction of sand movement. Grainfall laminae, comparable in steepness to less steep than grain-flow strata, arise as sand settles on moderately steep, typically concave-up slopes. Plane-bed laminations, formed during vigorous grain saltation over smooth, near-horizontal surfaces, form the third bedding type. Various lamination patterns arise when wind ripples migrate over near-horizontal to moderately inclined sand slopes. Various combinations of these basic strata can occur in beds ranging from a few decimetres to a few tens of metres in thickness, and are sensitive indicators of dune type and wind régime (e.g. Thompson 1969; Clemmensen 1987; Karpeta 1990; Sweet 1992).

Forest growth is favoured by climatic conditions in the equatorial, maritime, and cool temperate zones. Wind-blown trees (Allen 1992), preservable in peats (Skertchly 1877; Allen 1992), lignites (Potonié 1910) and coals (Wnuk & Pfefforkorn 1987), furnish in these regions over the last 375 Ma an important, but underexploited, medium-scale palaeowind indicator. Observing prostrate trees in peats exposed only in drains, Skertchly (1877) was content to record simply the alignment of the trunks. Allen (1992) measured the orientation of prostrate trees revealed on extensive, intertidal peat ledges, where the fall-direction was readily established (position of rootball, taper of trunk, branch density, branching angle). Pennsylvanian tree ferns examined by Wnuk & Pfefforkorn (1987) had either the canopy or roots still attached, also allowing the fall-direction to be decided unambiguously.

The small scale indicators of palaeowind direction are flutes and grooves, wind ripples and adhesion ripples. Flutes and grooves are elongated, wind-aligned features due to the natural sand-blasting of exposed gravel or outcropping rock (Greeley & Iversen 1985). They occur in cold as well as hot deserts and, in the rock record, should be associated with unconformity surfaces and with lagged alluvial-fan conglomerates. Wind ripples are ridges of sand or granules which, with a steeper facer to leeward and an internal cross-stratification, lie transverse to the wind (Allen 1982; Fryberger *et al.* 1992). They represent combined grain saltation and reptation, and grow in wavelength (centimetres to metres) with increasing wind speed and grain size (Anderson 1987). Adhesion structures form where sand is blown over damp surfaces (Kocurek & Fielder 1982; Olsen *et al.* 1989). They vary from wart-like features to transverse ridges, with a spacing of the order of 1 centimetre, and a steeper face to windward.

3. INDICATOR SAMPLING AND DATA HANDLING

(*a*) *Field sampling*

The prime requirements in the field sampling of directional indicators in regional and larger-scale studies are to (i) avoid geographical bias, and (ii) collect sufficient structural data from the strata to allow features in folded or faulted beds to be restored to their initial attitude. Geographical bias is avoided by hierarchical sampling, based on equal grid squares (Potter & Pettijohn 1977). In the case of aeolian cross-bedding, for example, data variance can then be examined: (i) within beds; (ii) between beds within exposures; (iii) between exposures in the same grid square; and (iv) between squares. If at each exposure the formation dip and strike have been measured, and if needed also the fold plunge, the cross-bedding can be successfully restored to the horizontal. As a final correction, reference to a palaeocontinental reconstruction (e.g. Smith & Briden 1977; Firstbrook *et al.* 1979) for an azimuthal rotation may be necessary.

The prime need when sampling a scalar indicator is also the avoidance of geographical bias. Boreholes could be sited on a regular grid, or natural exposures might be sampled at a uniform number per grid square. As with directional features, the whole grid may require rotation to account for post-depositional continental movement.

(*b*) *Data analysis*

The first requirement in the case of a scalar indicator is to contour the mapped data. Normals drawn experimentally to these lines then define theoretical flow paths of the transportable scalar property, as in the drawing of fluid streamlines by estimating equipotential lines (e.g. Francis 1975). The flow paths can be directly calculated, of course, by solving the Laplace equations for the original data and their coordinates.

Directional indicators call for a different approach, since they afford the azimuth of the feature. It is best to analyse a set of palaeowind azimuths by calculating the vector mean and a measure of spread (Mardia 1972). A significance test will then relate the sample to a model of randomness. In principle, vector mean values when mapped are tangential to a set of sand flow-paths, corresponding to the streamlines above.

(*c*) *Data presentation*

Whereas data on scalar indicators are conveniently presented as well as analysed as maps of contour and 'flow-path' lines, information from directional indicators calls for graphical display in addition to statistical analysis and cartographic presentation.

A simple graphical display, but ill-suited to circular data, is the linear histogram in which, for example, cross-bedding azimuths are grouped into equal angular classes. The equivalent circular histogram is the widely used form of rose diagram in which sector length denotes frequency (e.g. Potter & Pettijohn 1977). Nemec (1988), objecting to the use of length, preferred sector area, the sector radius becoming proportional to the square-root of frequency. Instead of adopting the circular histogram, grouped or individual data may be represented by a spoke diagram (e.g. Shotton 1937; Allen 1992), in which a spoke of length proportional to frequency is placed along each sector mid-line. This type of graphical display is useful for contemporary wind régimes (Chandler & Gregory 1973), where data on strength as well as direction are generally available. In the case of aeolian cross-bedding, the angle as well as the direction of dip help in the determination of dune type and wind direction. This indicator can be fully represented by plotting the poles to the cross-bedding stereographically (e.g. Reiche 1938; Glennie 1983; Karpeta 1990).

A simple and useful mapping device is to plot out the vector mean palaeowind direction by grid square (Potter & Pettijohn 1977). These maps may be smoothed either by calculating a moving average (Potter & Pettijohn 1977) or experimentally by hand to produce the equivalent of streamlines.

4. INTERPRETATION OF PALAEOWIND INDICATORS

(*a*) *Timescales*

Exactly what attributes of the past wind at a place does a palaeowind indicator reflect? This question cannot yet be answered fully. The contemporary environment teaches that the local wind fluctuates in strength and direction on many timescales, depending on the climatic setting.

At the smallest scale, the wind is turbulent and gusty, varying in strength and direction on a timescale of seconds (order 10^{-3} h). In some areas, the wind varies diurnally, and in others either storms or frontal systems may for lengthy periods sweep by daily or more or less every few days. Variation is now on a scale of order 10^1–10^2 h. Wind-blown trees are likely to be toppled or snapped in a matter of seconds, a virtually instantaneous process, but could experience a progressive weakening to a point of criticality over a substantial part of a storm. Wind and adhesion ripples also probably reflect events with a timescale only of hours. The establishment of comparatively stable areas of atmospheric high pressure, and seasonal changes in wind régime, introduce change on a scale of 10^3–10^4 h. This timescale is probable best represented by dune cross-bedding and by erosional flutes and grooves. We may strongly suspect, with some instrumental support over recent decades, that wind régimes in addition vary on decadal (order 10^5 h), century (order 10^6 h) and millenial (10^7) scales. Régimes of such duration are most likely to be expressed by the shape and orientation of dunes, yardangs and especially wind furrows, representing the integrated effects of many short-lived wind events. Scalar indicators, for example, bed thickness, seem to record either brief events, as in the case of volcanic eruptions (order 10^1–10^2 h), or régimes of long duration (10^6–10^7 h) which integrate very many individual erosional and accretionary episodes.

(*b*) *Threshold winds*

From a palaeowind indicator in the rock record, we can often infer not only wind direction but also gain some impression of wind strength. This is because many wind-related geological processes only begin at a characteristic threshold strength.

The threshold for the overthrow or snap of a contemporary tree is high – a mean wind speed at 10 m height of order 22 m s^{-1} (gale-severe gale) – and dependent on several factors (Allen 1992). The species is important, through its control of the anchoring root system, the mechanical properties of the root and stem wood, and the architecture of the visible tree (i.e. the vertical distribution of wind drag force). Also significant is the season, for the presence of leaves increases drag. Windblow is favoured by thin, moist and weak soils. The context of the tree, whether open-grown or in woodland, also affects the threshold. We lack direct knowledge of the resistance of extinct species, but on general ecological grounds their windblow threshold was similarly high. Hence studies of palaeowind using trees are likely to tell us only about the régime of the infrequent, strong winds.

A threshold must also be exceeded before sand and dust can become airborne (Greeley & Iversen 1985; Pye & Tsoar 1990). The precise value changes with the size, sorting, density, shape and surface character of the grains, and with the aerodynamic roughness of the ground, but is equivalent in the case of quartz to a friction velocity of 0.1–0.2 m s^{-1} at a grain diameter of about 80 μm, rising to about 0.5 m s^{-1} at 20 μm and 1 mm respectively. The minimum velocity corresponds to a wind speed at 10 m height of order 10 m s^{-1}, that is, to a fresh breeze. Hence the remaining directional indicators of palaeowind, together with the scalar indicators (except those related to volcanicity), only yield information on the régime of moderate and strong winds.

(*c*) *Effective and resultant winds*

Not only must a threshold be exceeded before many wind-related processes become operative, but the effectiveness of the wind typically is found to increase nonlinearly with the excess strength. This has implications, as yet little explored, for the process of inferring a mean palaeowind direction from indicators which, at least in principle, are likely to have become weighted in abundance and orientation according to wind strength.

The wind drag on a standing tree increases roughly as the wind speed squared. Although trees are neither overthrown nor snapped until the wind has become strong, there remains an achievable and substantial range of even higher wind speeds over which increasingly general damage can be expected in forests. Hence, where general damage has occurred, the distribution of tree fall-directions may be biased toward the directions of the strongest of the effective winds. Progressive exhaustion of the stock of standing trees, however, may for some events mean that little or no record is created of the extreme or later winds. Additional complications may arise where the strong wind is highly localized, as with a tornado felling trees in many different directions within a small area.

The rate of sand and dust transport by wind increases as the cube of the wind speed adjusted by a threshold speed or, alternatively, as the cube of the shear velocity adjusted by a threshold shear velocity (Greeley & Ivesen 1985; Pye 1987; Pye & Tsoar 1990). Fryberger (1979) consequently related dune forms, and Breed *et al.* (1979) regional patterns of dunes in sand seas, to a spoke diagram of potential sand transport, formed by weighting the duration of the wind of each direction and strength by the sand-transporting capability of that wind. A resultant potential sand-transport direction can thence be obtained which, although not dissimilar to the average unweighted wind direction for the same period, is not identical to it.

Yardangs, wind furrows, and flutes and grooves record natural sand-blasting. Reviews by Allen (1982) and Greeley & Iversen (1985) suggest that the sand-blasting rate, measured as the mass lost per unit area and time, increases broadly as the cube of the wind speed, provided that the airborne particles are not so concentrated as to interfere. The rate depends on many factors, however, including the properties of the minerals involved, whether ductile or brittle, and a threshold wind speed may also limit this process. As with dunes, the erosional indicators are more likely to reflect the resultant potential sand-transport direction than the unweighted mean wind.

5. EXAMPLES OF PALAEOWIND FIELDS

(*a*) *The mid Flandrian in southwest Britain*

Although windblown trees abound in the Flandrian coastal peat sediments of the British Isles (Godwin 1943; Carter *et al.* 1989) and France (Ters 1987), little attempt has so far been made to exploit them in palaeoclimatic studies of this critical epoch. Skertchly (1877) concluded that the Fenland trees had toppled under the influence of southwesterly prevailing winds. Working on peat ledges on the Welsh coast, Bibby (1940) was able to record the fall direction of many of the exposed trees. As with Skertchly, the data were not analysed statistically, but Bibby concluded that in one bed the trees had been felled by southwesterly winds but in another by northeasterly blows.

An attempt at a more systematic methodology was made by Allen (1992), who measured the fall-direction of 509 trees distributed in 18 peat beds exposed at 14 sites spread over about 100 km in the inner Bristol Channel and Severn Estuary (figure 1*a*). The peats occur in about the middle of the sequence (*ca.* 10–15 m thick) of estuarine sediments (figure 1*b*), apparently ranging in age between 6100 conventional radiocarbon years BP and 2180 years BP (figure 1*c*). The grand vector-mean fall-direction is 080°.

It is interesting to compare the spoke diagram for

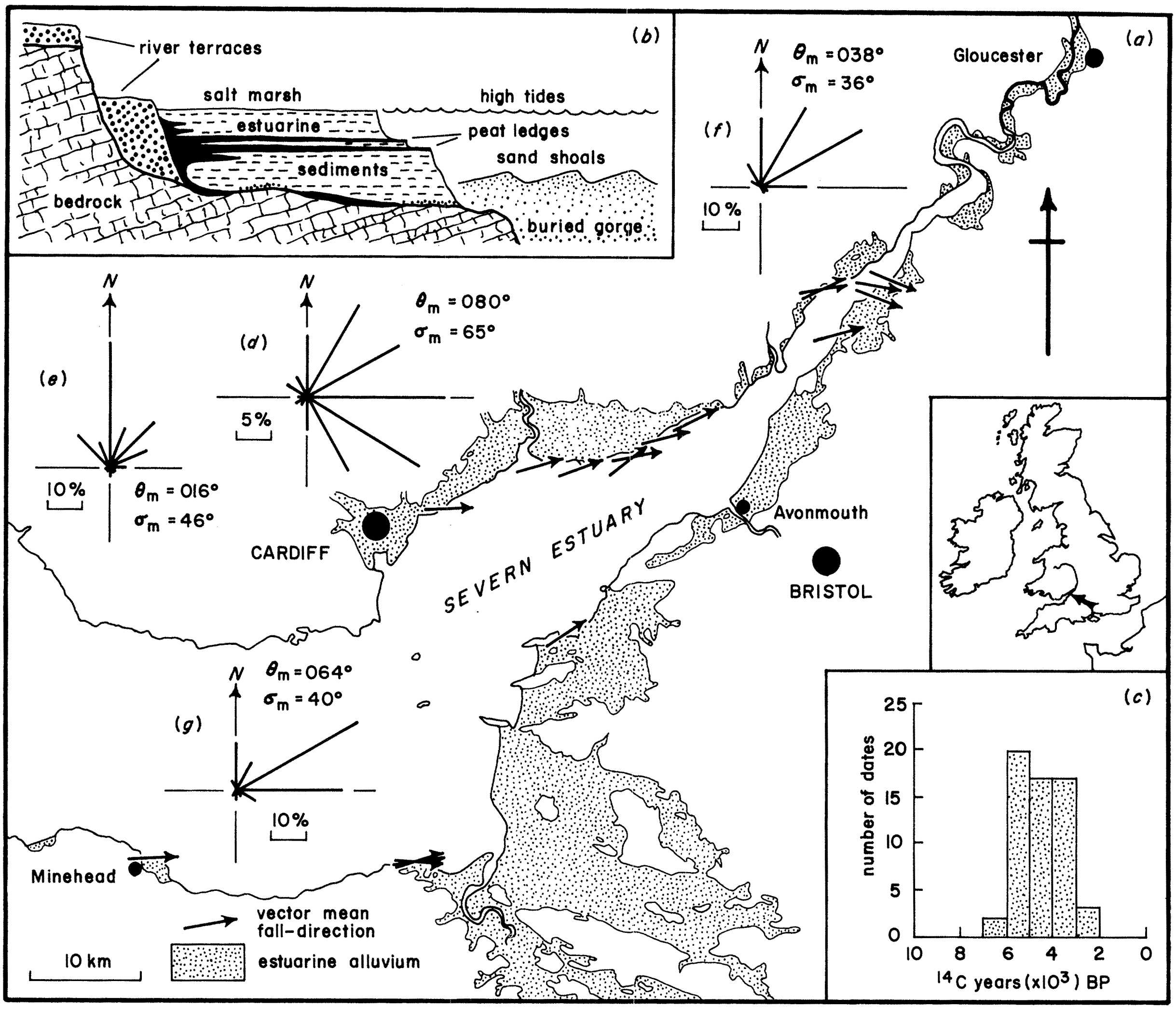

Figure 1. Fall-direction of mid Flandrian trees preserved in estuarine sediments of the inner Bristol Channel and Severn Estuary, southwest Britain. (*a*) Flandrian outcrops in the inner Bristol Channel and Severn Estuary and local vector-mean fall-directions. (*b*) Standard Flandrian stratigraphy for the inner Bristol Channel and Severn Estuary. (*c*) Frequency distribution of the conventional radiocarbon age of 59 mid Flandrian peats from the inner Bristol Channel and Severn Estuary. (*d*) Fall-directions of 509 mid Flandrian trees from the inner Bristol Channel and Severn Estuary. (*e*) Fall-directions of 580 trees brought down in southeastern England (2.2×10^6 ha) during the storm of 15–16 October, 1987. (*f*) Fall-directions of 73 trees brought down in Windsor Great Park (407 ha), Berkshire, during the storm of 15–16 October, 1987. (*g*) Directions of winds of a speed equal to or in excess of 28 kn (near gale and stronger), as recorded at Avonmouth during 1970–88. θ_m, vector-mean fall-direction; σ_m, standard deviation. Data and their sources given in Allen (1992).

these mid Flandrian trees (figure 1*d*) with trees felled in southeast England by the storm of 15–16 October 1987, at regional (figure 1*e*) and local levels (figure 1*f*), and with the corresponding wind rose for the strongest winds recorded over a recent 19-year period at Avonmouth (figure 1*a*,*g*). The data for southeast England, adjusted for the over-representation of one district (Allen 1992), come from the Windblown Tree Root Survey (Cutler *et al.* 1990). Although from a very much larger area, the spread of fall-directions for the 1987 storm event is substantially less than that of the mid Flandrian trees, which clearly record storms on many tracks and over a long period. There is a some similarity in fall-direction with the modern régime at Avonmouth, but again with a larger spread. Apparently the area was affected by the westerly zonal winds, as predicted by general circulation models (e.g. Kutzbach & Guetter 1986; COHMAP members 1988).

(*b*) *The Palaeozoic–Mesozoic of Europe and the U.S.A.*

More than a decade elapsed after Bigarella & Salamuni's (1961) pioneering study before others linked regionally distributed palaeowind indicators with palaeoclimate patterns. Glennie (1983) plotted cross-bedding directions from Permian dune sandstones in the North Sea area (*ca.* 800 × 900 km), at a palaeolatitude of about 10°N, the work of Laming (1966), Steele (1983), Clemmensen & Abrahamsen (1983), Clemmensen (1987) and Karpeta (1990) affording confirmatory or additional detail. The Permian winds apparently blew clockwise around a high-

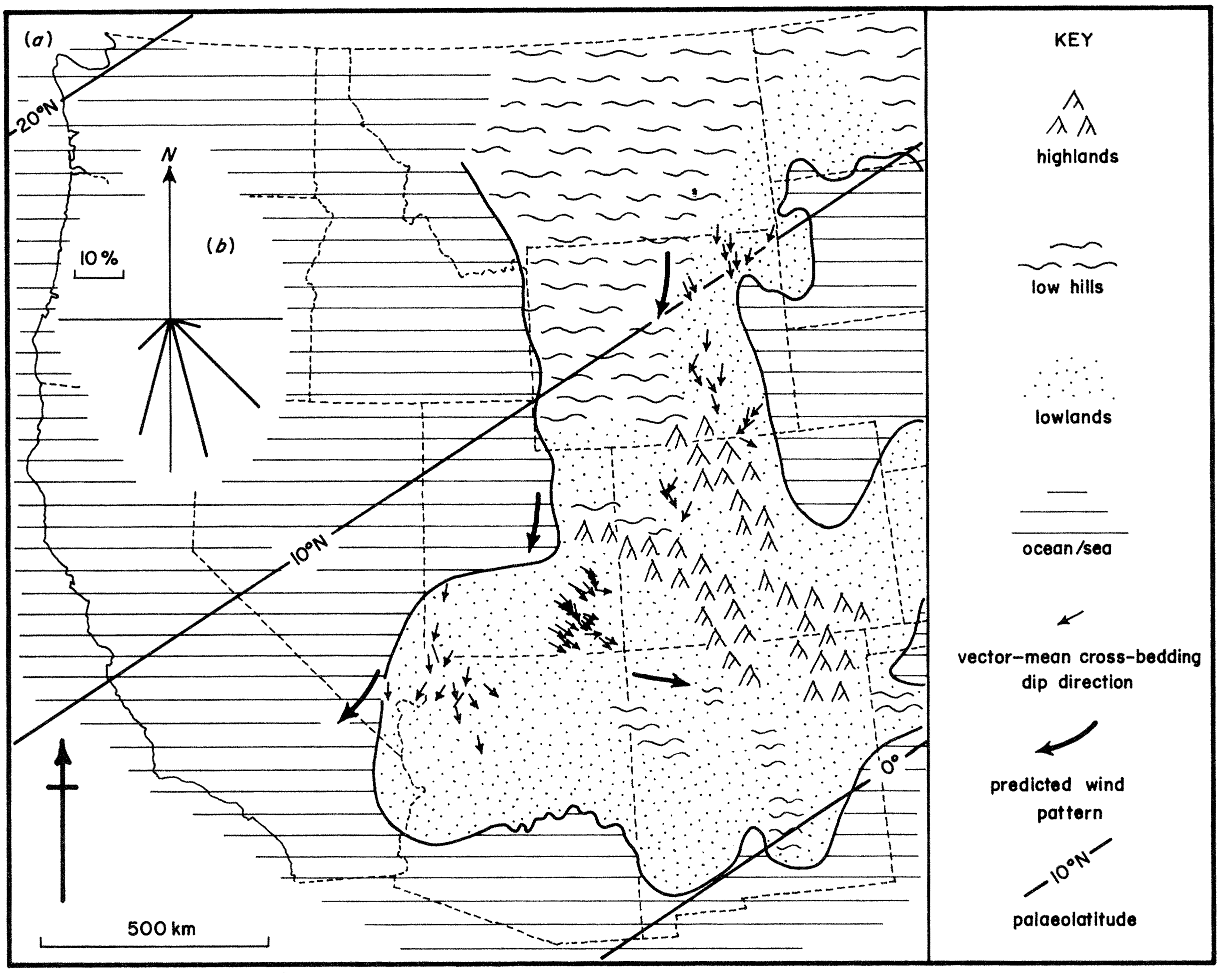

Figure 2. Early Permian (Wolfcampian) palaeowinds in the western United States of America. (*a*) Palaeogeography of the area with measured and predicted palaeowind directions. (*b*) Spoke diagram showing the distribution of 62 local vector-mean cross-bedding dip directions. After Peterson (1988, figures 6 and 7).

pressure region centered on the mid North Sea (but see Sneh (1988) for another interpretation). Aeolian sandstones frequently accumulated during a Palaeozoic–Mesozoic interval of about 150 Ma over a large part of the western U.S.A. (Blakey *et al.* 1988). Exploring the conceptual models of Parrish (1982) and Parrish & Curtis (1982), Peterson (1988) compared predicted winds with those inferred from cross-bedding at eight epochs within the above interval. The map for the early Permian (figure 2), exploiting cross-bedding from an area of about 400 × 1500 km, shows good agreement between the predicted and inferred palaeowinds, allowing for the inconclusive deflecting role of some highlands.

6. CONCLUSIONS

The variety of practical geological indicators of palaeowind currently exploitable is not great, but covers humid (little explored) as well as arid (traditional field of study) climates. When sampled systematically, and with the data treated statistically, they are capable of yielding reliable regional patterns of palaeowind. Because geological wind-related processes involve thresholds, and proceed nonlinearly, the vectors afforded may not correspond exactly with time-averaged wind directions.

This paper is Reading University PRIS Contribution Number 273.

REFERENCES

Ahlbrandt, R.S., Swinehart, J.B. & Maroney, D.G. 1983 The dynamic Holocene dune fields of the Great Plains and Rocky Mountain Basin. In *Eolian sediments and processes* (ed. M. E. Brookfield & T. S. Ahlbrandt), pp. 379–406. Amsterdam: Elsevier.

Allen, J.R.L. 1982 *Sedimentary structures*, 2 vols. Amsterdam: Elsevier.

Allen, J.R.L. 1992 Trees and their response to wind: mid Flandrian strong winds, Severn Estuary and Bristol Channel. *Phil. Trans. R. Soc. Lond.* B **338**, 335–364.

Anderson, R.S. 1987 A theoretical model for aeolian impact ripples. *Sedimentology* **34**, 943–956.

Bibby, H.C. 1940 The submerged forest at Rhyl and Abergele, North Wales. *New Phytol.* **39**, 220–225.

Bigarella, J.J. & Salamuni, R. 1961 Early Mesozoic wind patterns as suggested by dune bedding in the Botucatú Sandstone of Brazil and Uruguay. *Bull. geol. Soc. Amer.* **72**, 1089–1106.

Blakey, R.C., Peterson, F. & Kocurek, G. 1988 Synthesis of late Palaeozoic and Mesozoic eolian deposits of the Western Interior of the United States. *Sedim. Geol.* **56**, 2–125.

Breed, C.S. & Grow, T. 1979 Morphology and distribution of dunes in sand seas observed by remote sensing. *Prof. Pap. U.S. geol. Surv.* **1052**, 253–302.

Breed, C.S., Fryberger, S.G., Andrews, S., McAuley, C., Lennartz, F., Gebel, D. & Horstman, K. 1979 Regional studies of sand seas, using Landsat (ERTS) imagery. *Prof. Pap. U.S. geol. Surv.* **1052**, 305–397.

Brookfield, M.E. 1977 The origin of bounding surfaces in ancient aeolian sandstones. *Sedimentology* **24**, 303–332.

Carter, R.W.G., Devoy, R.J.N. & Shaw, J. 1989 Late Holocene sea levels in Ireland. *J. Quat. Sci.* **4**, 7–24.

Chandler, T.J. & Gregory, S. 1976 *The climate of the British Isles*. London: Longman.

Clemmensen, L.B. 1987 Complex star dunes and associated aeolian bedforms: Hopeman Sandstone (Permo-Triassic), Moray Firth Basin, Scotland. In *Desert sediments ancient and modern* (ed. I. Reid & L. E. Frostick), pp. 213–231. Oxford: Blackwell Scientific Publications.

Clemmensen, L.B. & Abrahamsen, K. 1983 Aeolian stratification and facies associations in desert sediments, Arran Basin (Permian), Scotland. *Sedimentology* **30**, 311–339.

COHMAP members 1988 Climatic change over the last 18,000 years: observations and model simulations. *Science, Wash.* **24**, 1043–1052.

Cooke, R.U. & Warren, A. 1973 *Geomorphology in deserts*. Los Angeles, California: California University Press.

Cutler, D.F., Gasson, P.E. & Farmer, M.C. 1990 The windblown tree survey: analysis of results. *Arboricult. J.* **14**, 265–286.

Eltayeb, I.A. & Hassan, M.H.A. 1992 Two-dimensional transport of dust from an infinite line source at ground level. *Geophys. J. Int.* **110**, 571–576.

Firstbrook, P.L., Funnell, B.M., Hurley, A.M. & Smith, A.G. 1979 *Palaeoceanic reconstructions, 160–0 Ma*. La Jolla, California: Scripps Institution of Oceanography, University of California.

Fisher, R.V. & Schmincke, H.-U. 1984 *Pyroclastic rocks*. Berlin: Springer-Verlag.

Francis, J.R.D. 1975 *Fluid mechanics for engineering students*, 4th edn. London: Edward Arnold.

Fryberger, S.G. 1979 Dune forms and wind regime. *Prof. Pap. U.S. geol. Surv.* **1052**, 137–185.

Fryberger, S.G., Hesp, P. & Hastings, K. 1992 Aeolian granule ripple deposits. *Sedimentology* **39**, 319–331.

Glennie, K.W. 1983 Early Permian (Rotliegendes) palaeowinds of the North Sea. *Sedim. Geol.* **34**, 245–265.

Godwin, H. 1943 Coastal peat beds of the British Isles and North Sea. *J. Ecol.* **31**, 199–247.

Goudie, A.S. 1983 The arid Earth. In *Megageomorphology* (ed. R. Gardner & H. Scoging), pp. 152–171. Oxford University Press.

Greeley, R. & Iversen, J.D. 1985 *Wind as a geological process*. Cambridge University Press.

Handy, R.L. 1976 Loess distribution by variable winds. *Bull. geol. Soc. Amer.* **87**, 915–927.

Hassan, M.H.A. & Eltayeb, I.A. 1991 Suspension transport of wind eroded sand particles. *Geophys. J. Int.*. **104**, 147–152.

Hunter, R.E. 1977 Basic types of stratification in small eolian dunes. *Sedimentology* **24**, 361–387.

Karpeta, W.P. 1990 The morphology of Permian palaeodunes – a reinterpretation of the Bridgnorth Sandstone around Bridgnorth, England, in the light of modern dunes studies. *Sedim. Geol.* **69**, 59–75.

Kocurek, G. & Dott, R.H. 1981 Distribution and uses of stratification types in the interpretation of eolian sand. *J. sedim. Petrol.* **51**, 579–595.

Kocurek, G. & Fielder, G. 1982 Adhesion structures. *J. sedim. Petrol.* **52**, 1229–1241.

Kutzbach, J.E. & Guetter, P.J. 1986 The influence of changing orbital parameters on surface boundary conditions on climate simulations for the past 18,000 years. *J. atmos. Sci.* **43**, 1726–1759.

Laming, D.J.C. 1966 Imbrication, palaeocurrents and other sedimentary features in the lower New Red Sandstone, Devonshire, England. *J. sedim. Petrol.* **36**, 940–959.

Lancaster, N. 1986 Grain size characteristics of linear dunes in the southwestern Kalahari. *J. sedim. Petrol.* **56**, 395–399.

Lancaster, N. 1992 Relations between dune generations in the Gran Desierto of Mexico. *Sedimentology* **39**, 631–644.

Lugn, A.L. 1968 The origins of loesses and their relation to the Great Plain in North America. In *Loess and related eolian deposits of the world* (ed. C. B. Schultze and J. C. Frye), pp. 139–182. Lincoln: University of Nebraska Press.

Mainguet, M. 1972 *Le modelé des grès*. Paris: L'Institut Géographique Nationale.

Mardia, K.V. 1972 *Statistics of directional data*. London: Academic Press.

McIlveen, R. 1991 *Fundamentals of weather and climate*, 2nd edn. London: Chapman & Hall.

McKee, E.D. (ed.) 1979*a* A study of global sand seas. *Prof. Pap. U.S. geol. Surv.* **1052**, 1–429.

McKee, E.D. 1979*b* Sedimentary structures in dunes. *Prof. Pap. U.S. geol. Surv.* **1052**, 83–134.

Nemec, W. 1988 The shape of the rose. *J. sedim. Petrol.* **59**, 149–152.

Olsen, H., Due, P.H. & Clemmensen, L.B. 1989 Morphology and genesis of asymmetric adhesion warts – a new adhesion surface structure. *Sedim. Geol.* **61**, 277–285.

Parrish, J.T. 1982 Upwelling and petroleum source beds, with reference to the Palaeozoic. *Am. Ass. Petrol. Geol. Bull.* **66**, 750–774.

Parrish, J.T. & Curtis, P.L. 1982 Atmospheric circulation, upwelling, and organic-rich rocks in the Mesozoic and Cenezoic eras. *Palaeogeogr. Palaeoclim. Palaeoecol.* **40**, 31–66.

Peterson, F. 1988 Pennsylvanian to Jurassoc eolian transport systems in the western United States. *Sedim. Geol.* **56**, 207–260.

Potonié, H. 1910 *Die Entstehung der Steinkohle und der Kaustbiolithe überhaupt*. Berlin: Verlag von Gebruder Borntraeger.

Potter, P.E. & Pettijohn, F.J. 1977 *Paleocurrents and basin analysis*, 2nd edn. Berlin: Springer-Verlag.

Pye, K. 1987 *Aeolian dust and dust deposits*. London: Academic Press.

Pye, K. & Tsoar, H. 1990 *Aeolian sand and sand dunes*. London: Unwin Hyman.

Pye, K. & Zhou, L.-P. 1989 Late Pleistocene and Holocene aeolian dust deposition in north China and the northwest Pacific Ocean. *Palaeogeogr. Palaeoclimat. Palaeoecol.* **73**, 11–23.

Rea, D.K. & Leinen, M. 1988 Asian aridity and the zonal westerlies: late Pleistocene and Holocene record of eolian deposition in the northwest Pacific Ocean. *Palaeogeogr. Palaeoclim. Palaeoecol.* **66**, 1–8.

Reiche, P. 1938 An analysis of cross-lamination – the Coconino Sandstone. *J. Geol.* **46**, 905–932.

Rubin, D.M. 1987 *Cross-bedding, bedforms and paleocurrents*. Tulsa, Oklahoma: Society of Economic Paleontologists and Mineralogists.

Ruhe, R.V. 1969 *Quaternary landscapes in Iowa*. Iowa State University Press.

Shotton, F.W. 1937 The Lower Bunter Sandstones of north Warwickshire and east Shropshire. *Geol. Mag.* **74**, 534–553.

Sarnthein, M. 1978 Sand deserts during glacial maxima and climatic optima. *Nature, Lond.* **272**, 43–46.

Skertchly, S.B.J. 1877 *Geology of the Fenland*. London: Mem. Geol. Surv. Gr. Br.

Smith, A.G. & Briden, J.C. 1977 *Mesozoic and Cenozoic palaeocontinental maps*. Cambridge University Press.

Sneh, A. 1988 Permian dune patterns in northwestern Europe challenged. *J. sedim. Petrol.* **58**, 44–51.

Snowden, J.O. & Priddy, R.R. 1968 Geology of Mississippi loess. *Miss. Geol. Surv. Bull.* **111**, 13–203.

Steele, R.P. 1983 Longitudinal draa in the Permian Yellow Sands of northeast England. In *Eolian sediments and processes* (ed. M. E. Brookfield & T. S. Ahlbrandt), pp. 543–550. Amsterdam: Elsevier.

Sweet, M.L. 1992 Lee-face airflow, surface processes, and stratification types: their significance for refining the use of eolian cross-strata as paleocurrent indicators. *Bull. geol. Soc. Am.* **104**, 1528–1538.

Ters, M. 1987 Variations in Holocene sea level on the French Atlantic coast and their climatic significance. In *Climate – history, periodicity and predictability* (ed. M. R. Rampino, J. E. Sanders, W. S. Newman & L. K. Königsson), pp. 204–237. New York: Van Nostrand Reinhold.

Tewes, D.W. & Loope, D.B. 1993 Palaeo-yardangs: wind-scoured desert landforms at the Permo-Triassic unconformity. *Sedimentology* **39**, 251–261.

Thompson, D.B. 1969 Dome-shaped dunes in the Frodsham Member of the so-called 'Keuper' Sandstone Formation (Scythian-?Anisian: Triassic) at Frodsham, Cheshire (England). *Sedim. Geol.* **3**, 263–289.

Wnuk, C. & Pfefferkorn, H.W. 1987. A Pennsylvanian-age terrestrial storm deposit: using plant fossils to characterize the history and process of plant accumulation. *J. sedim. Petrol.* **57**, 212–221.

Discussion

J. T. Parrish (*University of Arizona, U.S.A.*). I am a little sceptical over the use of tree-fall as indicative of palaeowind. Most strong-wind events capable of blowing down trees operate on small spatial and temporal scales and, in the case of the mid Flandrian, peat-related examples from the Severn Estuary described by Professor Allen, the trees were probably toppled from the soft substrate after death.

J. R. L. Allen. In reply to Professor Parrish, I would like to clarify that in the case of the Severn Estuary study: (i) the quality of woody tissues showed that the vast majority of the toppled trees were healthy when felled; (ii) the trees had tended to fall with a similar orientation in groups, as occurs in contemporary forests affected by strong winds; and (iii) the frequency distribution of fall-directions of the trees ($n = 509$) is closely similar to that of the directions of today's strong winds (near gale and stronger) in the area. I consider that there was no evidence from the mid Flandrian of the Severn Estuary for the view that the trees there had responded to wind in ways significantly different from those reported from contemporary forests, some known to be growing on peat. More research is required on the response of trees, individually and collectively, to strong winds, and a great deal remaines to be learned about the character of tree-felling winds (e.g. turbulence properties, coherent structures) and about the complex dynamical interaction between trees and the wind. Whereas some tree-felling events indeed affect very small areas at a time, others are much more substantial spatially. The storms associated with mid-latitude depressions, as can be expected to have affected the Severn Estuary during the mid Flandrian, are capable of damaging trees within an area totalling of the order of at least 10^7–10^8 ha at a time. The methodology proposed does not seek to draw inferences from the consequences of a single wind-event, but from the response of a forested area integrated over a substantial number of storms. The same principle will apply if palaeowinds are to be inferred from the distribution of volcanic ashes. The spatial thickness and grain-size patterns of such as loess, however, already represent an integration of many dust-transporting events over time.