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Magnetic fabric characteristics of bioturbated wave-produced grain orientation in the Bridport–Yeovil Sands (Lower Jurassic) of Southern England

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ABSTRACT

There is little visible primary hydrodynamic lamination preserved in the Bridport–Yeovil Sands as a result of intense bioturbation. Where lamination is present, it exhibits wave-produced characteristics, although current ripple lamination is also found. The grain orientation of a variety of bioturbated and non-bioturbated fine-grained sandstones has been determined by measuring the magnetic susceptibility anisotropy. The magnetic fabric is of a primary style and preserves two lineation directions approximately 90° apart in azimuth. These lineation directions are interpreted as the result of grain long-axis orientations produced by wave and current processes. The magnetic fabric is dominantly carried by a small proportion of paramagnetic minerals, thought to be largely detrital chlorite and micas. This magnetic fabric has been acquired by depositional alignment of the detrital phyllosilicates and by reorientation of the phyllosilicates during the early stages of compaction. The magnetic fabric of the intensely bioturbated sandstone is not significantly different in magnitude characteristics or in the preservation of lineation directions from that of the non-bioturbated sandstone.

INTRODUCTION

Quartz grain long-axis orientation has rarely been used as an aid in investigating the environmental conditions of deposition of sediments, primarily because of the time involved in measuring sufficient numbers of samples. Measurement of the anisotropy of magnetic susceptibility provides a method which is capable of approximating the overall preferred grain orientation of a bulk sample in 3-D (Hamilton & Rees, 1970; Hrouda, 1982). The technique is relatively quick (2 to 45 minutes per determination) allowing a large number of samples to be analysed, thus more fully representing the preferred grain orientation of the sediment as a whole.

Studies of sand shape fabrics produced by unidirectional currents generally find the grain long-axis orientation is parallel to the current direction (Rees & Woodall, 1975; Hiscott & Middleton, 1980). No studies have systematically examined the processes of grain orientation under oscillatory, wave-induced currents, yet the action of this depositional mechanism is increasingly being recognized in ancient sediments. Even in foreshore and backshore beach environments the long-axis orientation of grains is generally normal to the beach trend due to the respective action of swash and wind deposition (Curray, 1956; Taira, 1976). Nachtigall (1962) sampled sedimentary structures within the intertidal zone of the North Sea coast of Germany and found the grain long-axis orientation in symmetrical wave ripples was consistently directed parallel to the ripple crest. This type of orientation of particles is parallel to the orientation taken-up by shells and pebbles during wave transport and deposition (Nagle, 1967), and is the most-likely grain orientation to be observed in wave deposited sediments.

This contribution shows that wave-produced grain orientation appears to be important in the Lower Jurassic Bridport–Yeovil Sands, although its recognition relies upon the identification of wave-produced sedimentary structures.

THE BRIDPORT-YEOVIL SANDS

The Bridport–Yeovil Sands form a contiguous sand sheet largely restricted to the Wessex Basin (Fig. 1). The outcrop in Dorset and Somerset ranges in age from the *P. dispansum* subzone of the Toarcian to the *L. opalinum* subzone of the Aalenian. The unit is lithologically similar to the Toarcian sand body north of the Mendips structural high (Fig. 1), which spans parts of the *C. crassum* to *P. dispansum* subzones (Howarth, 1980). A localized development of cross-bedded biosparite, the Ham Hill Stone (Davies, 1969), is present west of Yeovil, and lithologically similar limestones are known from borehole material (Knox, Morton & Lott, 1982).

The Bridport–Yeovil Sands are up to 50 m thick and gradually coarsen upwards from silty mudstones to very fine-grained quartz wackes and arenites in the upper parts. Feldspar is present in minor amounts with small proportions of muscovite, biotite and

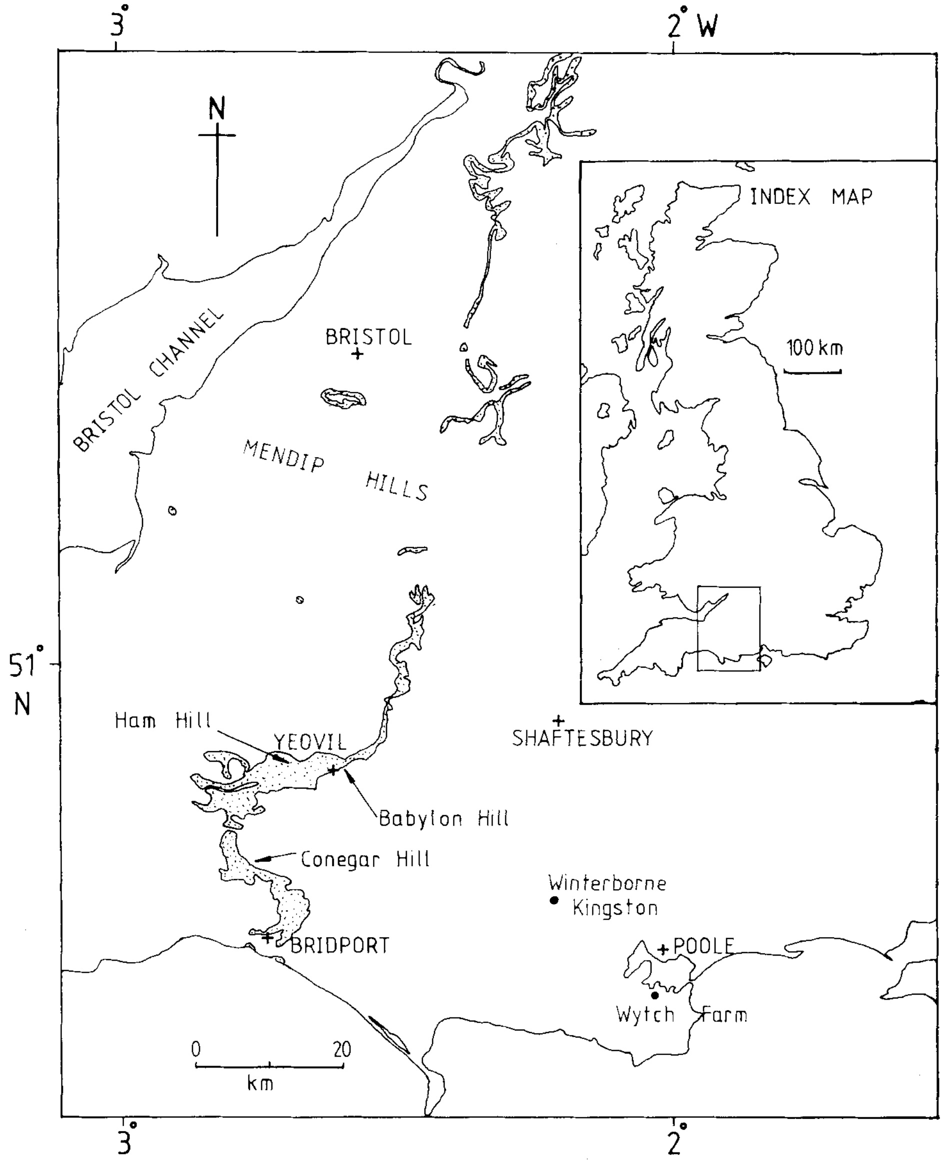

Fig. 1. Outcrop of the Upper Lias (stippled) and localities discussed in text.

chlorite (Davies, 1967). The clay matrix is dominated by kaolinite, illite and mixed layer clays, although significant amounts of smectite are also found (Corbin, 1981). A similar clay mineral assemblage has been reported in borehole material from Wytch Farm, with the addition of small amounts of vermiculite and clay chlorites (Morris & Sheppard, 1982). In contrast, Knox (1982) identified the dominant clay mineral in the Bridport Sands of the Winterborne Kingston borehole to be authigenic chlorite (derived from chamosite) with minor illite and kaolinite.

A notable feature of the sandstone is a regular alternation of cemented sandstones (calcareous sandstones) and poorly cemented sandstones (Fig. 2). The calcareous sandstones are generally laterally impersistent and at a number of localities form early diagenetic concretions up to 1·5 m in diameter. Mica flakes in the sandstones are largely crumpled due to compaction, whereas in the calcareous sandstones they infrequently show signs of distortion (Davies, 1967).

In the more bioclast-rich sandstones and uncommon limestone lithologies there is evidence of two generations of cement (Knox, Morton & Lott, 1982), an early blocky ferroan spar, probably a replacement of an original fibrous marine cement, and the dominant pore-filling, prismatic, strongly ferroan spar of late diagenetic origin (Campos & Hallam, 1979). The textural relationship of the cement and detrital grains suggests that the calcareous sandstones have suffered little fabric compaction (Davies, 1967; Knox, Morton & Lott, 1982).

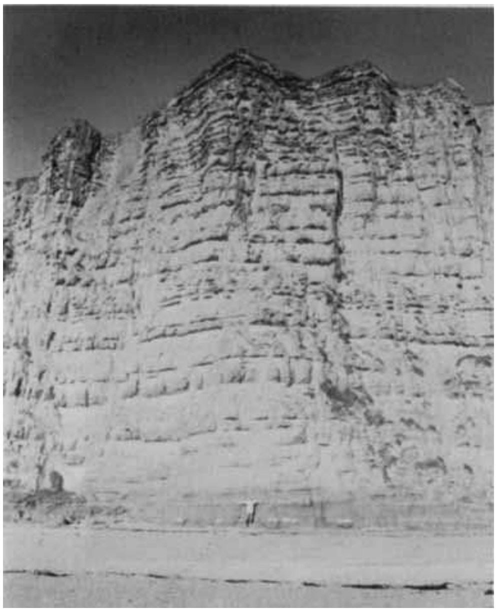

Fig. 2. Bridport Sands capped by the Aalenian and Bajocian Inferior Oolite at the top of the cliff, West Bay, Bridport.

SEDIMENTARY STRUCTURES

Bioturbation is pervasive and has led to the almost total destruction of hydrodynamic sedimentary structures (see Davies, 1969, for X-ray photographs of this bioturbation). Most of this burrowing has produced indefinite mottling but trace fossils *Thallasinoides*, *Chondrites*, *Siphonites(?)*, *Rhizocorallian* and *Arenicolites* can be seen locally. The sedimentary structures are visible due to sediment inhomogeneity resulting from muddy sandstone alternating on a mm scale with mud-poor sandstone.

Primary hydrodynamic sedimentary structures are rare in South Dorset exposures but are more common in the exposures of the *moorei* and *aalensis* subzones around Yeovil (Figs 3 & 4). The most abundant type of cross-stratification is small-scale, with cosets rarely thicker than 20 mm and low angle foresets, typically less than 15°. The lower bounding surface is scoop-shaped and the cross-lamination intricately interwoven, commonly dipping in opposing directions within the same horizon. In some exposures the cross-lamination is intimately associated with indistinct plane lamination and commonly passes into horizontal lamination or slightly undulatory plane laminae (see Davies, 1969; Fig. 18B). Horizontal lamination may pass laterally into shallow depositional troughs with an increase of lamina thickness, and pass into directionally opposed laminae on the opposite side of the trough. The origin of these structures is thought to be dominantly the result of wave processes (cf. Reineck & Singh, 1980; p. 103), although diagnostic structures such as cross-stratal off-shoots or bundle-wise upbuilding are rarely observed. Structures more typical of current processes such as herring-bone cross-bedding or shallow scoop-shaped channel-like features are comparatively uncommon. However, in some exposures it is difficult to unequivocally distinguish the mode of formation (wave or current) of the small-scale cross-lamination, due to the intense bioturbation and poor definition of the laminae. Hydrodynamic sedimentary structures are commonly grouped into layers with a relative lack of bioturbation. Locally these layers possess poorly defined (due to the bioturbation) erosional bases. Davies (1969) likewise noted alternations of bioturbated and non-bioturbated sedimentary structures in the Toarcian sands north of the Mendips.

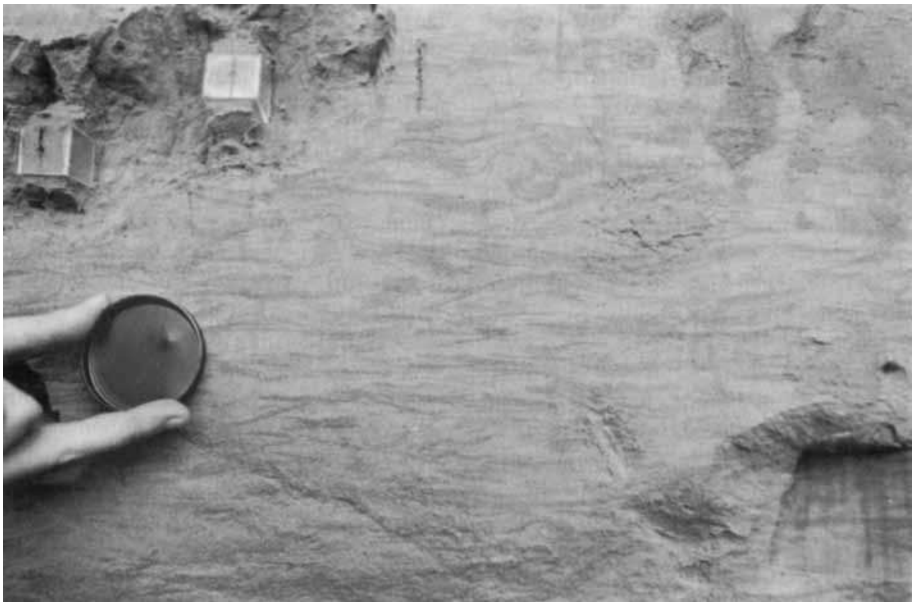

Fig. 3. Cross-lamination and undulatory plane lamination, dominantly of a wave-produced origin. Note the upward increase in the intensity of bioturbation, Site 3, Babylon Hill. Two *in situ* cubic samples are also shown.

Fig. 4. Lightly burrowed undulatory plane lamination and low angle cross-lamination of wave origin, resting abruptly on intensely bioturbated sandstone. Fallen block of calcareous sandstone, West Bay, Bridport.

Rare calcareous sandstones in the Yeovil area possess shell lags and erosional bases, with size grading of the bioclasts, suggestive of deposition by storm events. The Bridport–Yeovil Sands can therefore be considered as the deposits of a wave-dominated, storm-influenced shelf below fairweather wave base.

MAGNETIC FABRIC

The magnetic fabric is usually visualized as a triaxial susceptibility ellipsoid (Hrouda, 1982), the major, intermediate and minor axes of which are represented in magnitude and direction by the maximum (K_{max}), intermediate (K_{int}) and minimum (K_{min}) principal susceptibility axes. In most sedimentary rocks this ellipsoid is oblate and aligned such that the K_{min} axis is vertical. The direction of preferred grain long-axis orientation is parallel to the K_{max} axis. The shape of the susceptibility ellipsoid is described by the ratio of the magnetic lineation and foliation, the q value, where:

$$q = \frac{K_{max} - K_{int}}{K_{max} + K_{int} - 2(K_{min})}.$$

The total percentage susceptibility anisotropy is represented by the parameter $h\%$, where:

$$h\% = \frac{(K_{max} - K_{min}) \times 100}{K_{int}}.$$

It has proved possible to formulate certain criteria which are characteristic of a depositional style of magnetic fabric (Hamilton & Rees, 1970). In these fabrics the q value is usually less than 0·7 and the angular deviation of the K_{min} axis from palaeovertical less than 25°. If samples have values outside these limits they are normally considered to possess a secondary style of magnetic fabric (Hamilton & Rees, 1970).

The magnetic fabric of a sediment can arise from a number of different magnetic minerals which it is important to identify, since their mineralogy and mode of incorporation in the sediment has considerable bearing upon the characteristics of the magnetic fabric (Owens & Bamford, 1976).

MAGNETIC MINERALOGY

In the present study the magnetic mineralogy has been investigated using oil immersion reflection microscopy, X-ray diffraction, thermomagnetic analysis, isothermal remanence acquisition (IRM), torque-field relationships and rotational hysteresis (Collinson, 1983). The carriers of the magnetic susceptibility have also been investigated by preparing magnetic separates.

The magnetic torque has been found to be approximately linearly related to the square of the applied field (Fig. 5), indicating that the susceptibility anisotropy is dominantly carried by paramagnetic minerals (Owens & Bamford, 1976). However, in most samples examined there appears to be a small ferromagnetic saturation component present in the curves at applied fields of less than 0·3T. The ferromagnetic properties of the Bridport–Yeovil Sands are dominated by detrital ferromagnetic ferrianilmenite, which has a coercivity dominantly below 0·3T. A considerably smaller ferromagnetic contribution is derived from Fe-rich titanomagnetite. The detrital ilmenite has undergone extensive diagenetic dissolution and conversion to rutile, and has a mean grain size of 40 μm.

The mineralogy of the magnetic separates indicates which minerals are likely to dominate the susceptibility of samples. This information, combined with the magneto-mineralogical data, and some inferences about the minerals' crystallographic orientation, indicate which minerals contribute to the magnetic fabric. The mineralogy of the magnetic separates is dominated by ilmenite, chlorite and muscovite/illite, with smaller amounts of goethite (derived from the weathering oxidation of pyrite at outcrop) and garnet.

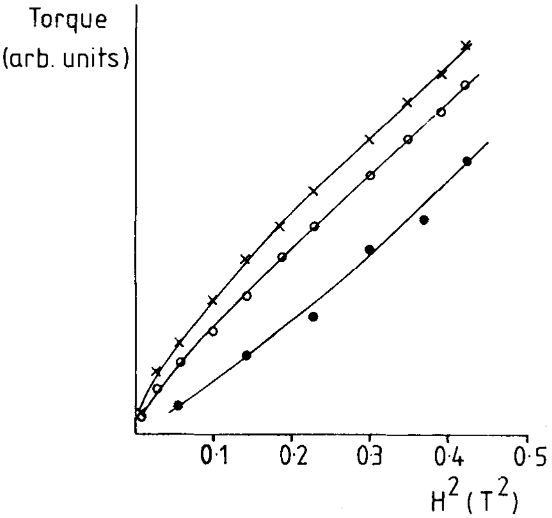

Fig. 5. Magnetic torque versus H^2 for sandstone samples from Babylon Hill (crosses) and Conegar Hill (circles), and a calcareous sandstone sample from Conegar Hill (filled circles).

Paramagnetic minerals do not possess shape-induced susceptibility anisotropy (Uyeda *et al.*, 1963), but must possess both crystalline susceptibility anisotropy and a preferred crystallographic orientation to contribute to the magnetic fabric (Hrouda, 1982). A contribution is not possible for garnet since it is magnetically isotropic, and is also unlikely for paramagnetic ilmenite, since microscopic observation of the magnetic separates show it to be equant in shape and consequently unlikely to assume a preferred crystallographic orientation upon deposition.

The small saturating component present in torque curves at fields of less than 0·3T (Fig. 5), indicates a small, perhaps shape induced component from ferri-anilmenite, even though this mineral is dominated by crystallographic susceptibility anisotropy (Uyeda *et al.*, 1963). Paramagnetic goethite (Hedley, 1971) is not thought to be a significant component of the magnetic fabric, since samples which do not contain oxidized pyrite have a magnetic fabric resembling samples which contain oxidized pyrite.

The susceptibility of samples from the Bridport–Yeovil Sands was found to be closely related to the clay content, such that those samples with the largest susceptibility are siltstones. This, and their abundance in the magnetic separates, suggests that the susceptibility is primarily linked to the abundance of phyllosilicates. Iron-bearing phyllosilicates are known to possess both appreciable susceptibilities (Collinson, 1983) and crystalline susceptibility anisotropies (Ballet & Coey, 1982; Ballet, Coey & Burke, 1985). Hence, micas (muscovite, illite) and chlorites are the most likely sources of the observed susceptibility anisotropy. Possible mechanisms are explored later to account for the acquisition of this magnetic fabric.

SAMPLING AND MEASUREMENT TECHNIQUES

Three sampling techniques have been used in this study:

(a) Drill core samples (Collinson, 1983) 25 mm in diameter were drilled at outcrop and from hand samples in the laboratory;

(b) The copper-tube technique of Townsend & Hailwood (1985) was used to sample poorly indurated sandstones and siltstones;

(c) Where the above two techniques could not be applied, cubic samples (16 mm or 25 mm) were prepared at outcrop using a non-magnetic stainless steel knife (Townsend & Hailwood, 1985). These samples were cut to fit inside perspex holders (Fig. 3), protected from disintegration by thin plastic film.

The magnetic fabric of these samples has been measured using a low field torque magnetometer (Collinson, 1983) in which the lower limit of anisotropy of susceptibility detection is $1{\cdot}3 \times 10^{-12}$ SI units for a sample of volume 10^{-5} m^3.

The susceptibility anisotropy of samples from the Bridport–Yeovil Sand is close to the detection limit of this instrument, and it has therefore been necessary to apply certain modifications to standard methods of determination of the susceptibility ellipsoid. The perspex and glass holder system used to support the sample during measurement has a small susceptibility anisotropy which has to be subtracted from the susceptibility anisotropy signal of the sample plus holder. Since the samples have such weak anisotropies, small errors in the measurement of the deflections on the torque magnetometer can result in large errors in the specification of the susceptibility ellipsoid (King, 1967). A procedure has been developed (similar to that of King, 1967) which repeatedly applies the above two corrections to the sample signal and calculates the mean susceptibility ellipsoid. In this procedure the K_{min} axes are averaged by Fisher statistics (Collinson, 1983) and samples are rejected from analysis if the Fisher angular standard deviation is greater than 25°. The K_{max} axes declinations are averaged by Von Mises statistics (Mardia, 1972), with samples rejected from analysis of the lineation directions if they fail the Rayleigh test (Mardia, 1972) at the 99 per cent confidence interval. It is valid to use these averaging procedures because the shapes of the susceptibility ellipsoids are strongly oblate and therefore distributions of K_{max} and K_{min} axes are approximately described by these statistics (cf. King, 1967). The K_{max} inclinations, $h\%$ and q values are averaged by normal statistics (mean q is the $\log_{10}$ mean). Using these procedures it has been possible to reject those samples from analysis which may have been unduly affected by instrumental errors and uncertainties.

SAMPLING LOCALITIES

Sampling has been concentrated in two localities (Fig. 1):

(a) Babylon Hill near Yeovil (Torrens, 1969);

(b) Conegar Hill near Broadwindsor (Richardson, 1928–30).

Both sections are within the *aalensis* subzone. Samples have also been collected from other exposures at Ham Hill (ST 481162), Burton Bradstock (SY 485891), East Chinnock (ST 499135), Barrington (ST 395178) and Bradford Abbas (ST 567142). These samples are dominantly from the *moorei* and *levesquei* subzones.

RESULTS

(i) Babylon Hill

Sampling was restricted to the relatively unbioturbated parts of this section (Fig. 6a). The magnetic fabric of those samples which pass the reliability criteria (the criteria based on the primary fabric characteristics and the stringent instrumental criteria) are shown in Fig. 7a. Twenty-two samples were measured from Site 1, 36 from Site 3 and 10 from Site 4. In addition, the long-axis orientation of quartz grains was measured optically (in a plane parallel to the bedding) in 1 sample from Site 2 and 4 samples from Site 4, on oriented polished sections. The long-axis orientation of the quartz grains was assessed by the parallel lines method (Bonham & Spotts, 1971), using a binocular microscope with a mechanical stage and grid method of grain selection. The mean quartz grain long-axis orientation for these samples is in a NE–SW orientation, agreeing with Davies' (1969)

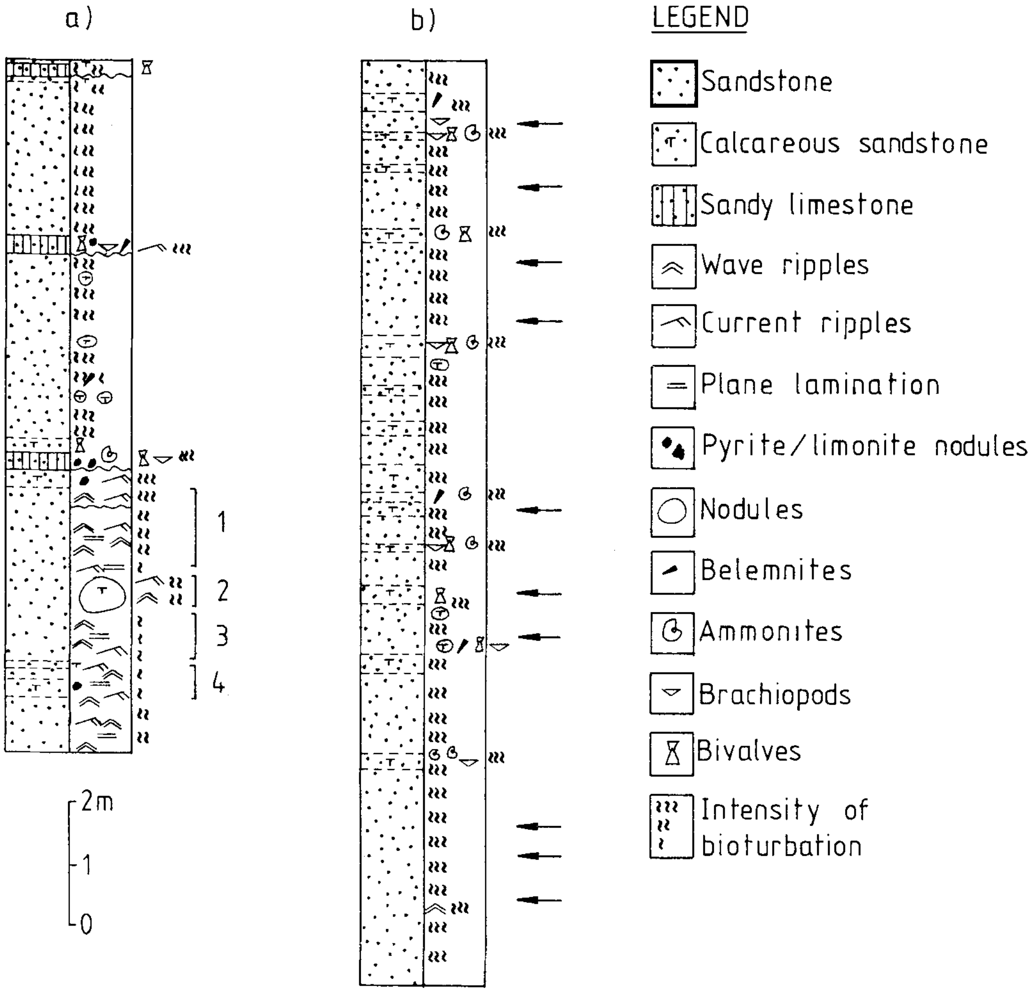

Fig. 6. Sedimentological logs and location of sampling sites for (a) the Babylon Hill and (b) Conegar Hill sections (Sites indicated by arrows).

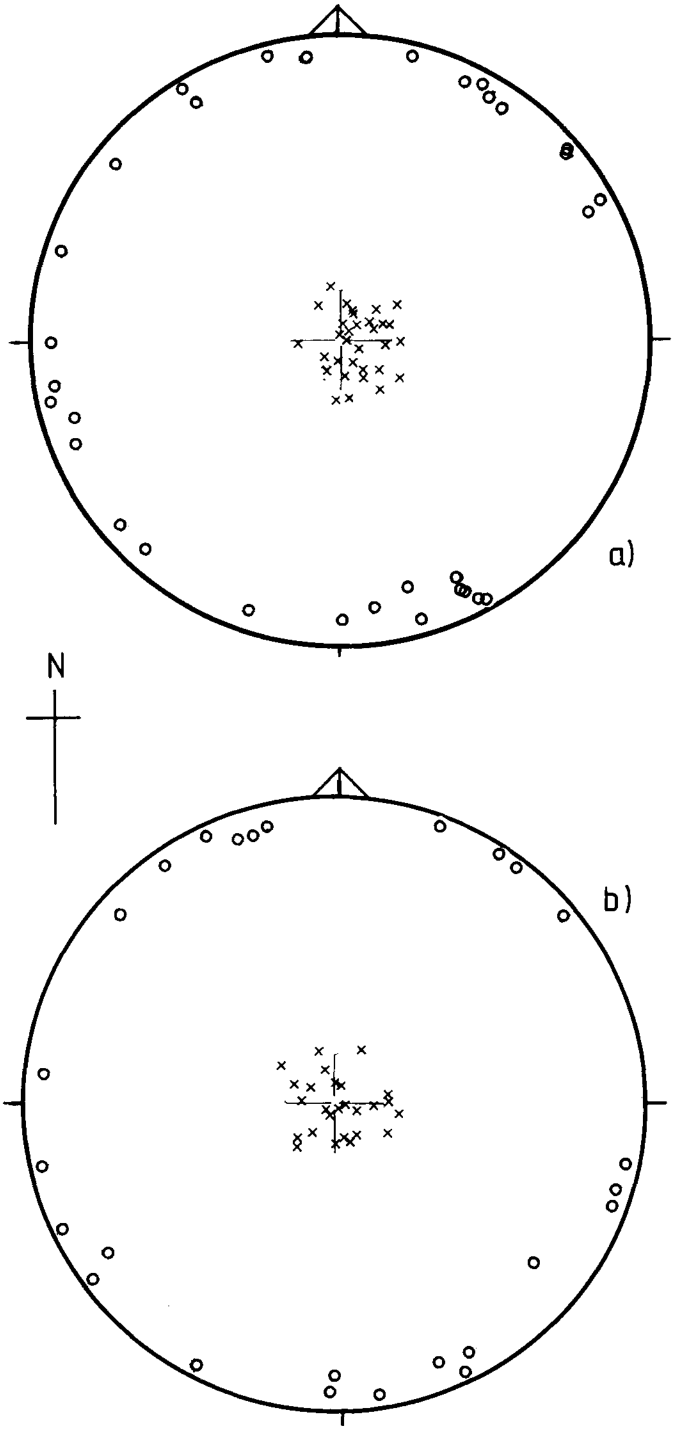

Fig. 7. Upper hemisphere equal area stereographic projections of magnetic fabric data (for samples passing reliability criteria) for (a) Babylon Hill and (b) Conegar Hill. ○, $K_{\max}$; ×, $K_{\min}$.

mean cross-lamination dip-direction for the Toarcian Sands (Fig. 8e & f).

(ii) Conegar Hill and other sections

Thirty-eight samples were collected from the Conegar Hill section at various stratigraphic levels (Fig. 6b). The sandstones in this section are richer in mud matrix than those in the Babylon Hill section. The magnetic fabric of those samples which pass the reliability criteria are shown in Fig. 7b. A total of 20 samples were collected from other sections, which were principally from bioturbated sandstone or siltstone.

DISCUSSION

Before the directional data are discussed, it is important to consider how the minerals giving rise to the magnetic fabric could be preferentially oriented. Large detrital micas will be oriented parallel to bedding during deposition, giving rise to an oblate magnetic fabric due to their crystalline susceptibility anisotropy (cf. Hrouda, 1982; Hounslow, 1985). However, smaller phyllosilicates are not likely to be oriented by currents.

Hounslow (1985) has suggested a mechanism whereby the magnetic fabric of detrital, clay-sized, paramagnetic phyllosilicate minerals in mudrocks could be acquired during compaction. The magnetic fabric acquired in this way may reflect both the compaction-induced preferred orientation of these minerals and the primary preferred quartz grain long-axis orientation. In this model the magnetic foliation reflects the influence of compaction and its passive rotation of the phyllosilicate platelets parallel to the bedding. The lineation reflects the distortion, by compaction, of these platelets around the quartz grains, producing a lineation in the direction of the quartz grain long-axis orientation. As such, the model suggests that the magnetic fabric shape parameters reflect the degree of preferred crystallographic alignment of these minerals; larger $h\%$ and smaller q values

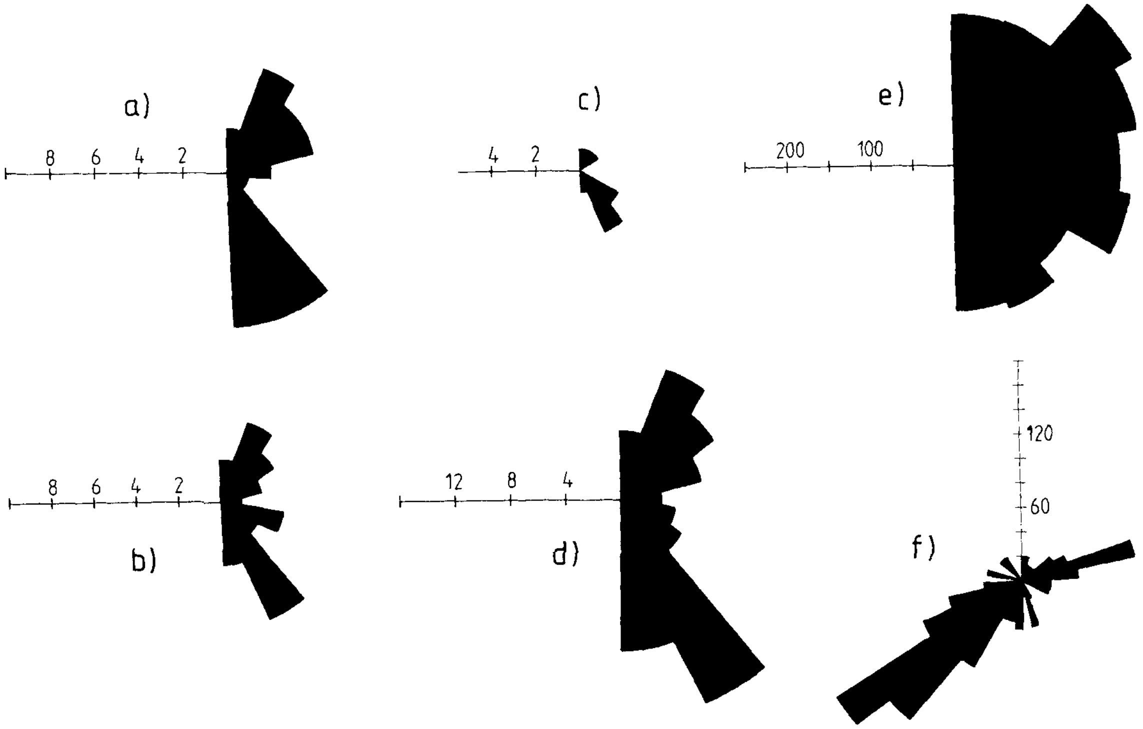

Fig. 8. 'Current direction' indicators. Magnetic fabric K_{max} axis azimuths for (a) Babylon Hill, (b) Conegar Hill, (c) other sections and (d) all sites together. (e) Preferred quartz grain long-axis orientation, measured optically, for samples from Babylon Hill. (f) Cross-lamination dip directions for the Bridport–Yeovil Sands (from Davies, 1969).

for larger degrees of preferred crystallographic alignment parallel to the bedding. The process of compaction could give rise to a similar type of fabric in the larger micas, by their compactional distortion around the quartz grains. Indeed, large micas in the magnetic separates (typically 80–800 μm in size) are crumpled and fractured due to bending around the smaller quartz grains. A test of the detrital versus compactional orientation mechanisms is provided by a comparison of the fabric of the calcareous and non-calcareous sandstones.

Petrologic evidence suggests that the calcareous sandstones have suffered little compaction, and therefore the fabric should reflect the preferred depositional alignment of the phyllosilicates. Conversely, the fabric of the sandstones should reflect both the depositional alignment of the detrital micas and any compactional reorientation. However, the magnetic fabric magnitude parameters for sites in calcareous sandstones (Conegar Hill) are apparently similar to those in the sandstones (Table 1), suggesting that the degree of preferred alignment is not significantly different and compactional reorientation is minimal.

The expected effect of bioturbation on a depositional magnetic fabric is an increase in the magnitude and variability of q, a decrease in $h\%$, and an increase in between sample scatter of $K_{\min}$ and $K_{\max}$ axes (Rees, 1970; Hamilton & Rees, 1970). Such a relationship seems to hold for sites 1 and 3 at Babylon Hill, although in comparison to the sandstones at Conegar Hill this relationship does not hold. Indeed, the most intensely bioturbated lithologies are siltstones sampled at Barrington, which have the smallest grain size and q values of the sampled sections, suggesting compaction may be controlling the fabric in the muddier lithologies (cf. Hounslow, 1985).

The data indicate both depositional and compactional orientation of the phyllosilicates with the controlling mechanism being decided by the grain size and proportion of clay. Depositional alignment is more likely in the coarser-grained and better sorted lithologies, and compactional alignment in the finer-grained lithologies.

Azimuthal distributions of $K_{\max}$ axes for these sites are shown in Fig. 8, and indicate the presence of two lineation directions:

(a) a NE–SW mode which agrees approximately with Davies' (1969) mean cross-lamination dip direction;

(b) a stronger mode approximately 90° to this.

The compatibility of lineation directions with Davies' (1969) mean cross-lamination dip directions, and the consistency between sampling localities, suggest that the lineations are reflecting a quartz grain long-axis orientation. The lineations are not appreciably different between the bioturbated and non-bioturbated lithologies, an observation which is not unique, since other studies have shown that bioturbated sediments may show a 'primary' type of magnetic fabric preserving the lineation (e.g. Rees *et al.*, 1982). However, these studies were different in respect that the magnetic fabric is carried by titanomagnetite, in contrast to the paramagnetic carriers in this study.

In the light of the presence of wave-produced

Table 1. Mean magnetic fabric parameters for each site. ASD is the Fisher angular standard deviation of the samples with primary fabrics. N is the number of samples measured.

LOCALITY	VOLUME SUSCEPTIBILITY (x 10^{-6} SI UNITS)	ASD OF K_{MIN} AXES	q	STANDARD DEVIATION OF q	h%	N	% WITH SECONDARY FABRIC	% REJECTED
Babylon Hill:								
Site 1	72	14.1	0.31	0.19	2.8	22	32	50
Site 3	72	8.8	0.18	0.19	3.2	36	5	51
Site 4	73	49.1	0.21	0.16	2.3	10	20	70
Conegar Hill:								
Calcareous Sandstone	89	14.0	0.19	0.28	2.8	18	11	39
Sandstone	92	11.8	0.19	0.28	2.5	20	5	30
Ham Hill	99	11.1	0.18	0.35	3.5	9	0	66
Bradford Abbas	73	8.7	0.39	0.07	5.4	4	50	50
East Chinnock	57	-	0.36	0.37	13.5	3	66	66
Barrington	111	7.2	0.12	0.35	4.1	2	0	50
Burton Bradstock	93	11.1	0.21	0.30	2.9	2	0	0

sedimentary structures in the Bridport–Yeovil Sands, which Davies (1969) failed to recognize, it is considered likely that Davies' data on cross-lamination dip directions may reflect wave-produced, as well as current-produced structures (Fig. 8f). The Ham Hill limestone (interpreted as a subtidal channel deposit) shows trough cross-bedding with coset heights of 0·2 m and a dominant foreset dip to the NE (Davies, 1969). The cross-bedding possesses clay and sand drapes up to 0·15 m thick over cosets, attesting to the transitory nature of the generating currents. The directional trend of this cross-bedding suggests that bi-directional currents were present along the same trend as that generating the cross-lamination. It is tempting to compare the cross-bedding trend in the Ham Hill limestone to the Toarcian and Aalenian ironstones in NE France (Teyssen, 1984), since both are of a similar trend, perhaps indicating similar current regimes. The magnetic fabric data show a dominant SE–NW lineation which would be expected if the wave translation direction was to the NE or SW, and the grain orientation was produced by waves. The magnetic fabric lineations and grain long-axis orientations, with a NE–SW trend, are interpreted as the result of unidirectional currents, although so little is known about grain orientation under conditions of oscillatory flow that this trend may also have been controlled by oscillatory currents. It is clear from the grain orientation and magnetic fabric data at Babylon Hill that there was significant temporal variability in the processes giving rise to the two lineation modes, perhaps related to storm events.

CONCLUSIONS

The magnetic fabric lineations are considered to reflect grain orientations dominantly produced by oscillatory, wave-induced currents, although the recognition of this is based entirely on the form of the sedimentary structures. The effect of even quite intense bioturbation upon the lineation directions is minimal. The lineation directions are consistent with published cross-lamination dip directions, attesting to the fact that consistent grain orientations can be preserved and measured in apparently bioturbated sandstone. The magnetic fabric of the Bridport–Yeovil Sands is dominantly carried by paramagnetic minerals, of which micas and chlorites are thought to be the most important. The magnetic fabric represents a measure of the preferred crystallographic orientation of these phases, and is thought to be produced by both depositional alignment and compactional rearrangement of the phyllosilicates. The grain size characteristics of the sandstone may be important in determining which of these processes is dominant.

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