End of the Kiaman Superchron in the Permian of SW England: Magnetostratigraphy of the Aylesbeare Mudstone and Exeter groups.

Mark W. Hounslow, Gregg McIntosh, Richard A. Edwards, Deryck Laming, Vassil Karloukovski

Supplementary Data

The data here is composed of:

Table s1: Sampling site details, and mean magnetic properties.
Figure s1. The new bed-division of the Littleham Mudstone Fm, placed onto the photographs of the cliff outcrops.
Figure s2. Rose diagrams of the AMS Kmax axes, in the Aylesbeare Mudstone Group, against the sediment logs of the section.
Figure s3. The spatial variation in the AMS Kmax axes, of all Permian-Triassic west of Sidmouth, placed onto their sampling sites, and the palaeocurrent directions inferred from the sedimentology.
Figure s4. Component A data, and details of demagnetisation characteristics.
Figure s5. Additional rock magnetic data, pertaining to magnetic mineralogy
Figure s6. Petromagnetic data for all palaeomagnetic specimens.
Figure s7. Virtual geomagnetic pole data for Permian Europe, and a discussion of how the new data here fits with this data.
References.

Section	No. on Fig 1	Grid ref	Lat/long	Bedding strike/dip	N_H	J_0 ($x10^{-3}$ A/m)	κ_{lf} ($x10^{-5}$ SI)	Formation/unit
Budleigh Salterton to Littleham Cove	1	SY040802 to SY063817	50.622N: -3.342W	302/5	38	3.2	2.1	Littleham Mudstone Fm (LMF)
Straight Point to Maer	2	SY040802 to SY011799	50.608N: -3.376W	340/5 to 013/8	60	4.0	1.35	Exmouth Mudstone and Sandstone Fm (EMSF), base of LMF
Sowden Lane to Lympstone Harbour	3	SX990836 to SX988842	50.638N: -3.441W	321/9 to 315/8	10	2.1	3.3	Base of EMSF, top of Exe Breccia Fm
Clyst St Mary Garage	4	SX976910	50.710N: -3.454W	045/5	2	2.4	0.68	Dawlish Sandstone Fm
Bishops Court Quarry	5	SX965915	50.711N: -3.465W	045/5	6	0.74	0.57	Dawlish Sandstone Fm
Langstone Rock	6	SX980779	50.598N: -3.445W	293/8	6	2.8	7.6	Exe Breccia Fm
Dawlish Station	7	SX964767	50.580N: -3.465W	293/10	5	1.4	2.7	Teignmouth Breccia Fm
Coryton Cliff and Cove	8	SX962762	50.577N: -3.468W	319/10	8	1.5	1.9	Teignmouth Breccia Fm
Holcombe Beach	9	SX957746	50.562N:-3.475W	342/12	2	2.4	5.1	Teignmouth Breccia Fm
Ness Point to Bundle Head	10	SX941720 to SX937712	50.533N: -3.500W	355/0 to 295/5	6	7.2	9.8	Oddicombe Breccia Fm
Maidencombe Beach	11	SX928684	50.505: -3.514	275/10 to 346/6	5	9.3	7.0	Oddicombe Breccia Fm
Whitsand to Watcombe Beachs	12	SX927674	50.496: -3.515	315/41 to 288/25	5	5.8	6.4	Watcombe Fm and Oddicombe Breccia Fm
West Sandford	Not on Fig. 1	SS811027	50.812N: -3.689W	105/14	1	10.8	12.1	Knowle Sandstone Fm

Table. s1. Section and site details sampled, and average magnetic properties of the samples. NH number of sampled horizons, Jo= Initial natural remanent magnetisation intensity, klf= low frequency magnetic susceptibility. Most samples were collected from the sea cliffs, with those from Bishops Court Quarry from a working quarry (Table s1). Those from Dawlish Station and West Sandford were from small cuttings. Samples from below bed B to the base of bed A (Fig. 5), in the Exmouth Mudstone and Sandstone Fm, were from foreshore exposures and sea-cliffs, east of Exmouth. In the breccia units, suitable units for palaeomagnetic sampling were thin, discontinuous sandstone and mudstone beds.

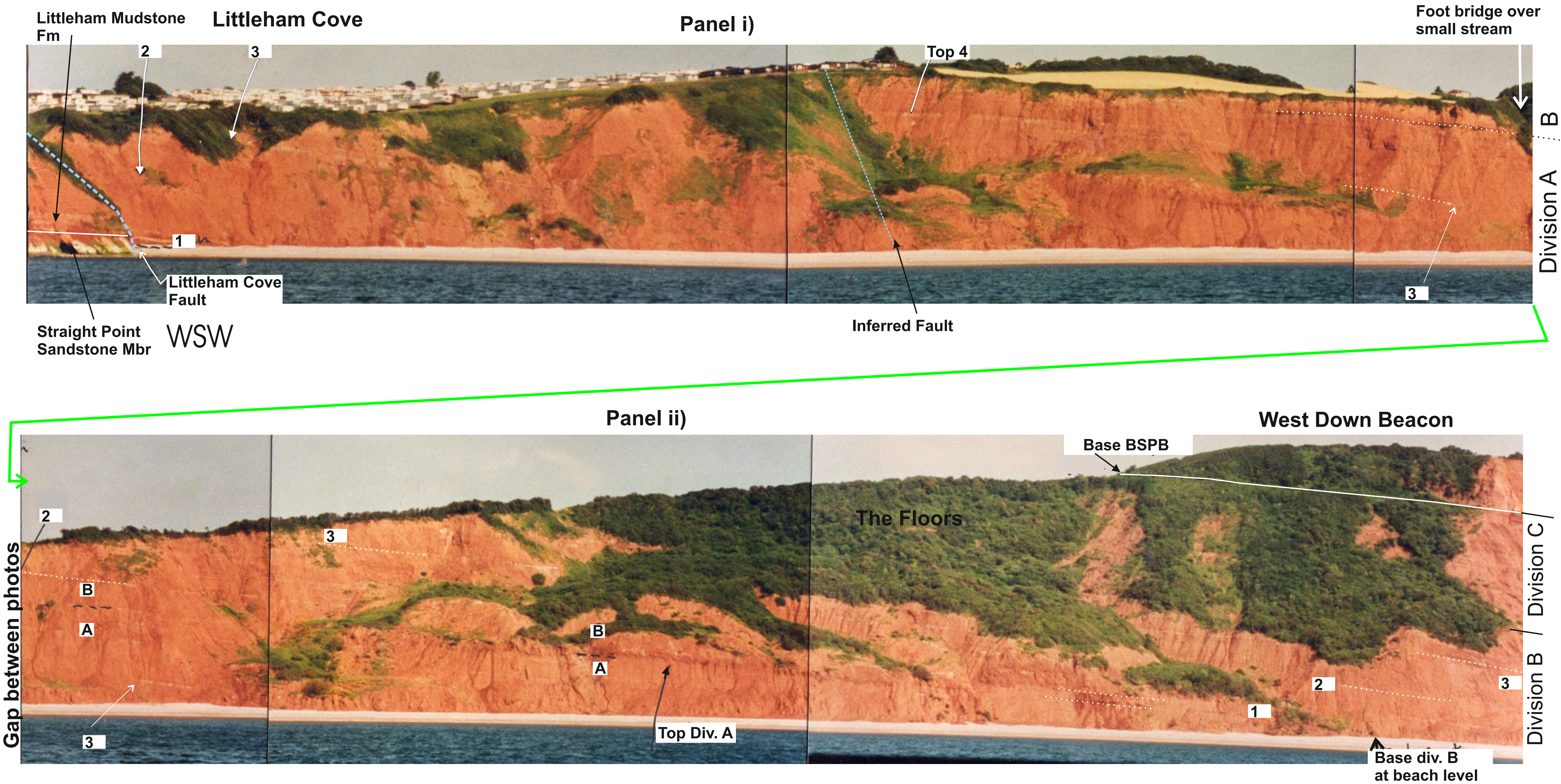


Fig.s1. Annotated photos of the cliff between Littleham Cove (panel i) and Budleigh Salterton (panel iv), indicating the bed and division sub-division of the Littleham Mudstones Formation. The three sub-divisions are a lower division A, mid division B, and an upper division C. The oldest part of the division A is exposed on the west side of the Littleham Cove fault. The W-E correlation across the Littleham Cove fault is not entirely clear, but the three sandstone beds (bed -1 in division A) may correlate to the upper-most units exposed west of the fault in the cliff adjacent to the path down the cliff. The succession is interrupted by a number of small landslips, which make the stratigraphy difficult to follow at beach level, without the photographs. The full succession can be examined by using the headwall scars behind the landslips.

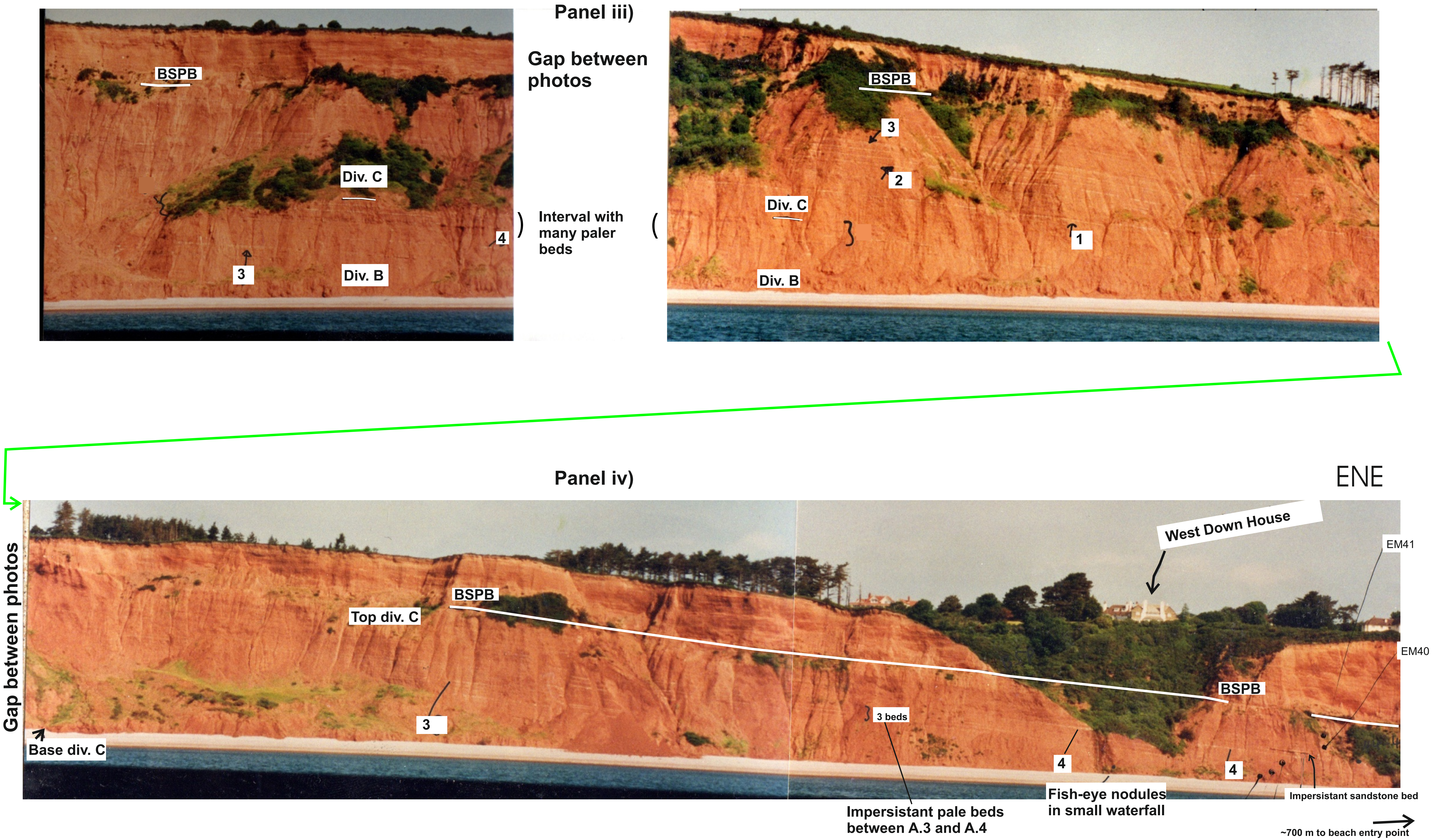


Fig.s1. Panels iii) and iv)

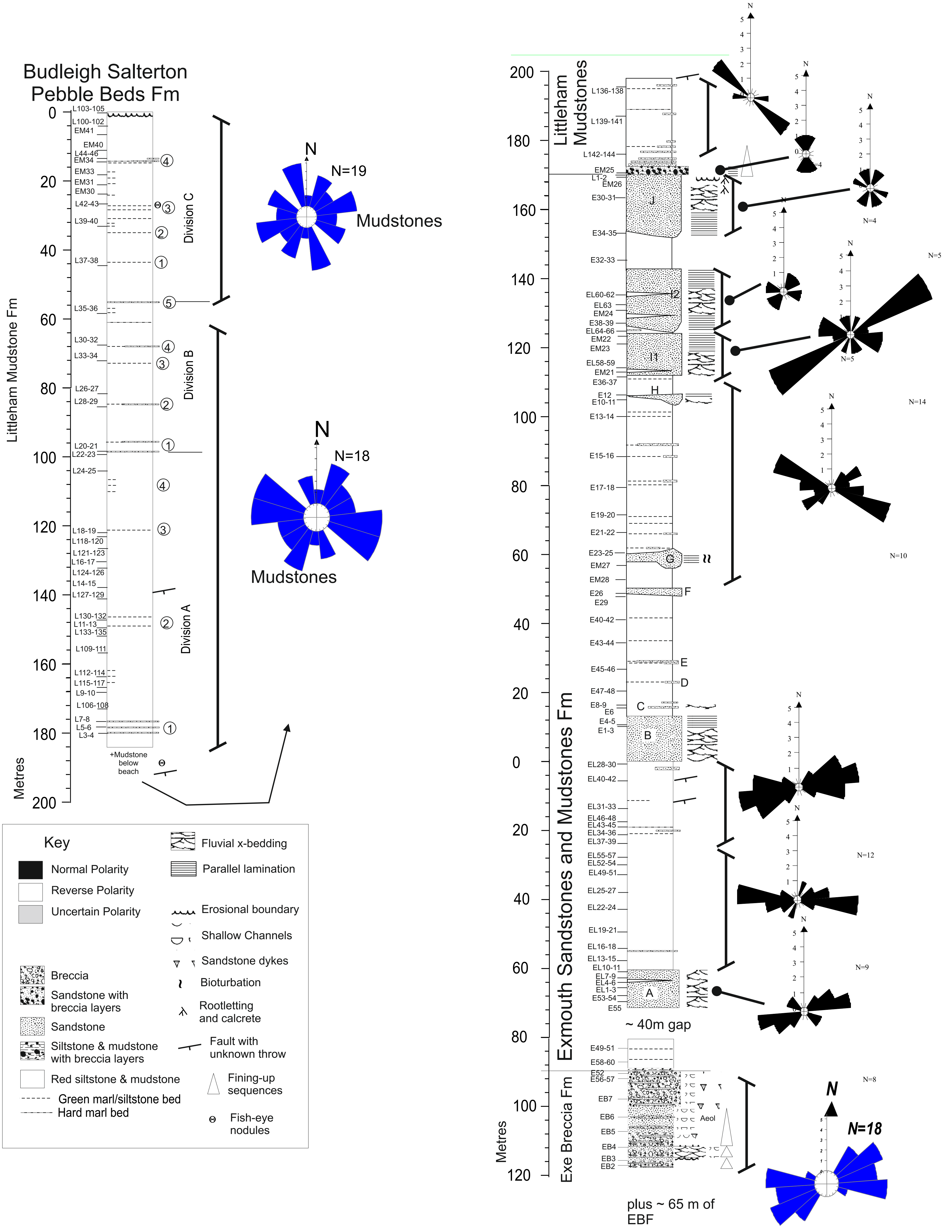


Fig.s2. K_{max} axis directions for samples from the Aylesbeare Mudstone Group. The directions have been mirrored about the 0-180 axis. The K_{max} axes directions illustrate the similarity in ENE or easterly flow directions between the Exe Breccia and the lower part of the Exmouth Mudstone and Sandstone Fm. The directions in the upper part of the Group are more variable, but likely indicate a more NE direction of sediment transport. The SE-NW Kmax axes trends seen in the mudstones above bed G, and particularly in the Littleham Mudstones Fm may represent NW directed wind transport of the clay and silt in these units.

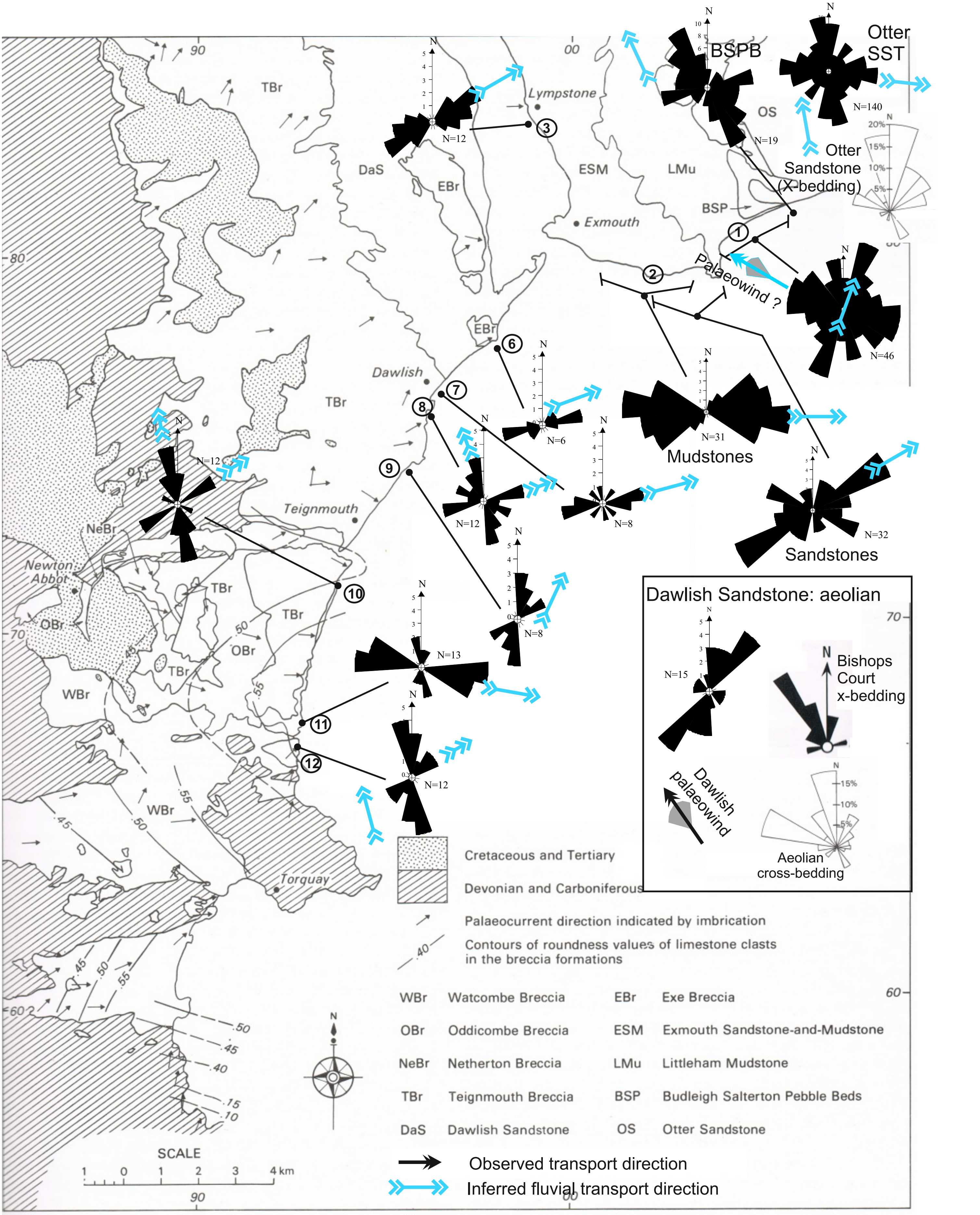
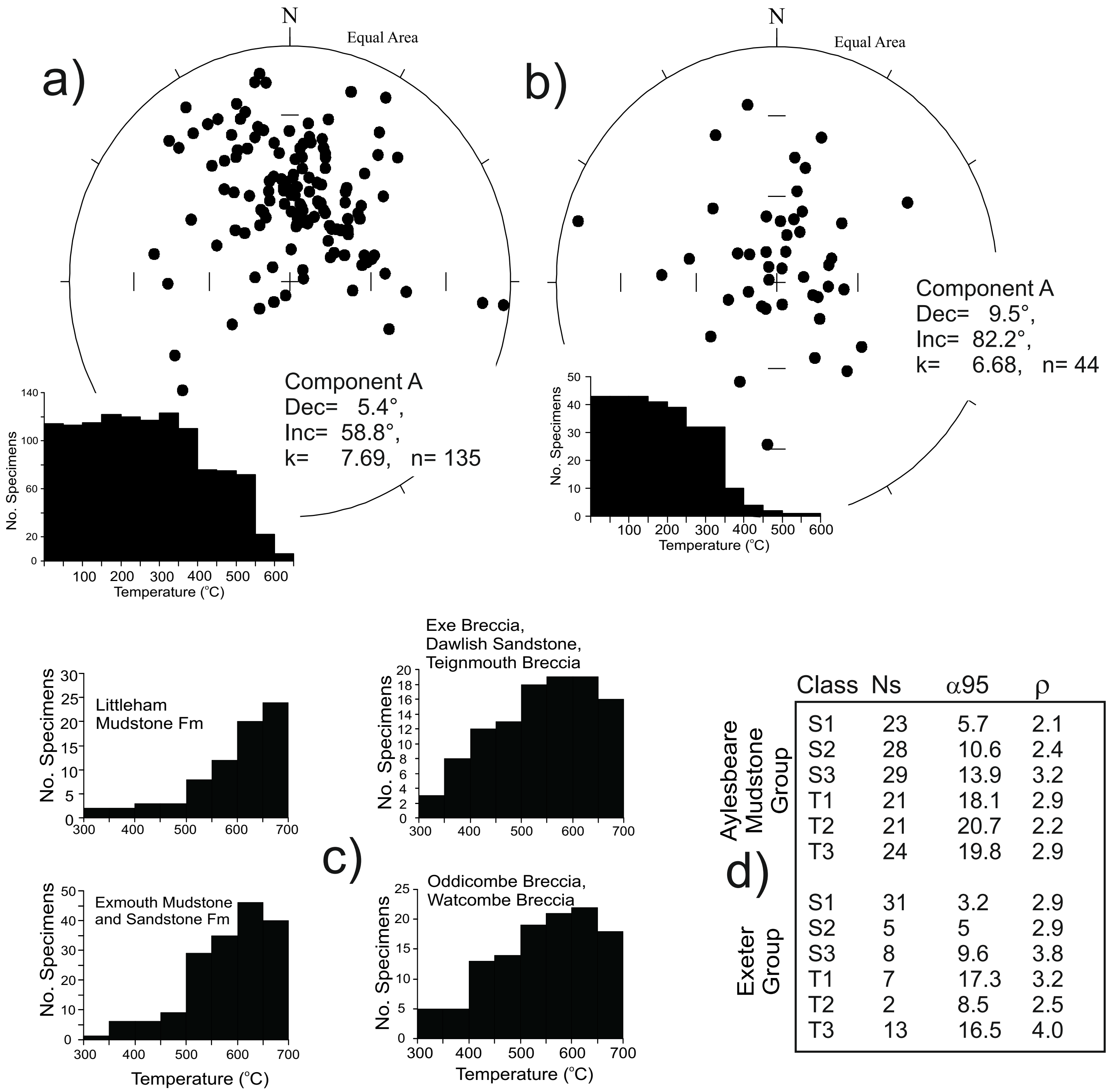


Fig.s3. Summary of transport directions and K_{max} axis directions for samples from the entire Permian, and Triassic successions west of Budleigh Salterton. Inset shows data for aeolian units, from the Dawlish Sandstone Fm (from Jones 1992, Selwood *et al.* 1984). The Kmax directions have been mirrored about the 0-180° axis (fluvial transport data from Laming 1966; Henson 1971; Selwood *et al.* 1984; Smith & Edwards 1991). The Triassic AMS data (Otter Sandstone, Budleigh Salterton Pebble Beds, BSPB) is from the samples described by Hounslow & McIntosh (2003). The Exeter Group below the Dawlish Sandstone Fm typically has bi-modal groups inferred to display ENE to easterly fluvial transport and northerly transport. Its possible in some of the sandstone and mudstones, the northerly trend may be a wind-transport direction, like seen in the aeolian units in the Dawlish Sandstone. Fluvial units in and above the Dawlish Sandstone Fm into the lower Aylesbeare Mudstone Group, show strong ENE to easterly fluvial transport. In the Littleham Mudstone Fm directions may be transitional to the northerly transport clearly seen in the overlying BSPB and Otter Sandstone.



	Class	Ns	α95	ρ
Aylesbeare Mudstone Group	S1	23	5.7	2.1
	S2	28	10.6	2.4
	S3	29	13.9	3.2
	T1	21	18.1	2.9
	T2	21	20.7	2.2
	T3	24	19.8	2.9
Exeter Group	S1	31	3.2	2.9
	S2	5	5	2.9
	S3	8	9.6	3.8
	T1	7	17.3	3.2
	T2	2	8.5	2.5
	T3	13	16.5	4.0

Fig.s4. Cumulative unblocking spectra for, a), b) the component A directions, from a) the Aylesbeare Mudstone Group, b) Exeter Group. C) The characteristic remanence ranges divided into stratigraphic groups. D) Statistics relating to the demagnetisation class, the number of specimens (Ns), the average α_{95} of the line (S-class) or plane (T-class) principle component fits, and the average excess standard deviation (ρ).

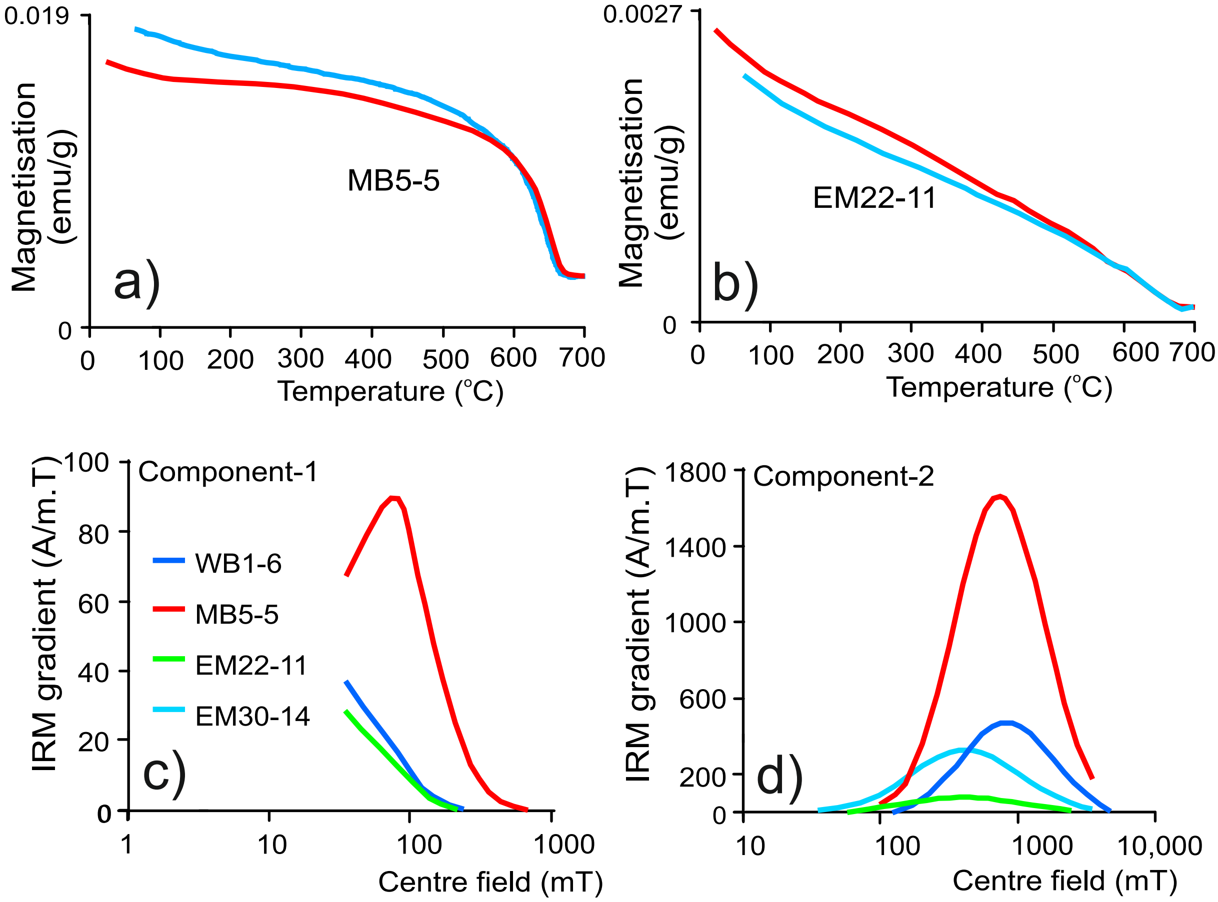
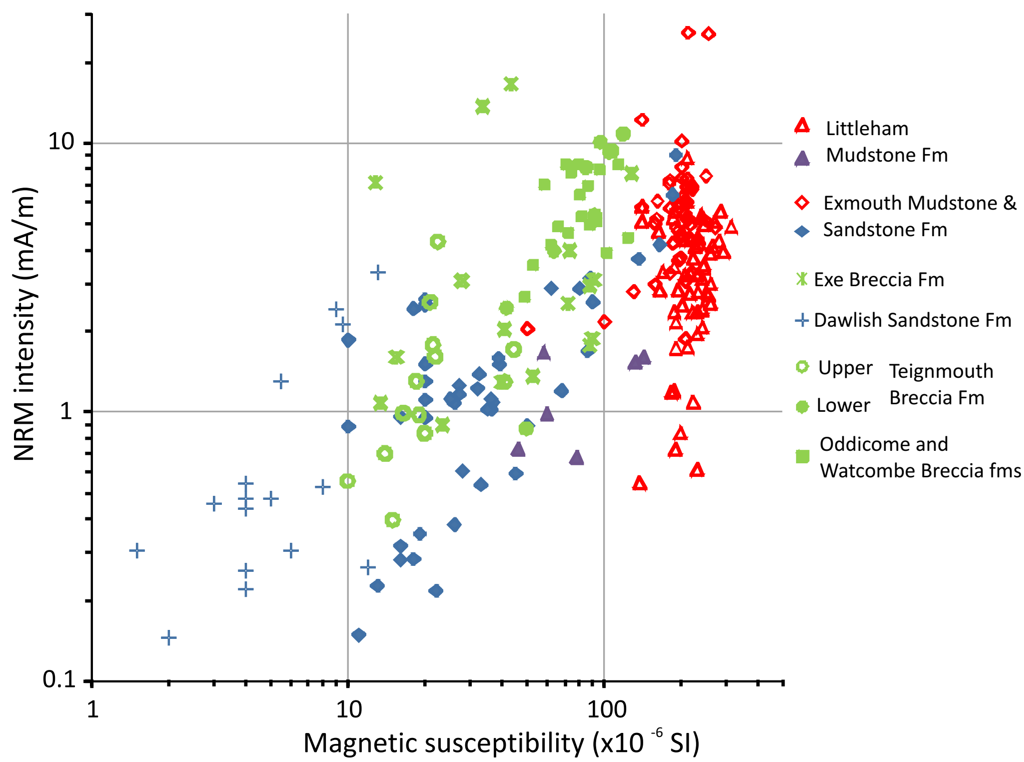


Fig.s5. A,b) Representative thermomagnetic data, measured using the vertical field translation balance (red=heating, blue= cooling). A subtle change in slope is seen at temperatures less than 200°C, which disappears when the estimated paramagnetic contribution is subtracted from the curves. C), d) log-Gaussian isothermal remanent magnetisation coercivity distributions (Kruiver *et al.* 2001) for selected samples, showing the fitted low field (component-1, c)) and high field components (component 2, d)). IRM data obtained with backfield data. Specimen WB1-6 and MB5-5 have higher coercivities (Bcr* of 741-851 and 63 mT for the 2 components) than EM22-11 and EM30-14 (Bcr* of 407-417 and 32 mT). Furthermore, these former 2 specimens had wider high coercivity distributions (dispersion parameter of 0.40-0.45 as compared to 0.32 for EM22-11 and EM30-14).

Fig.s6. Petromagnetic data for the Exeter and Aylesbeare Mudstone groups. Sandstone samples in blue, mudstone samples in red, and sandstone & sandy-mudstone units from breccia units in green.



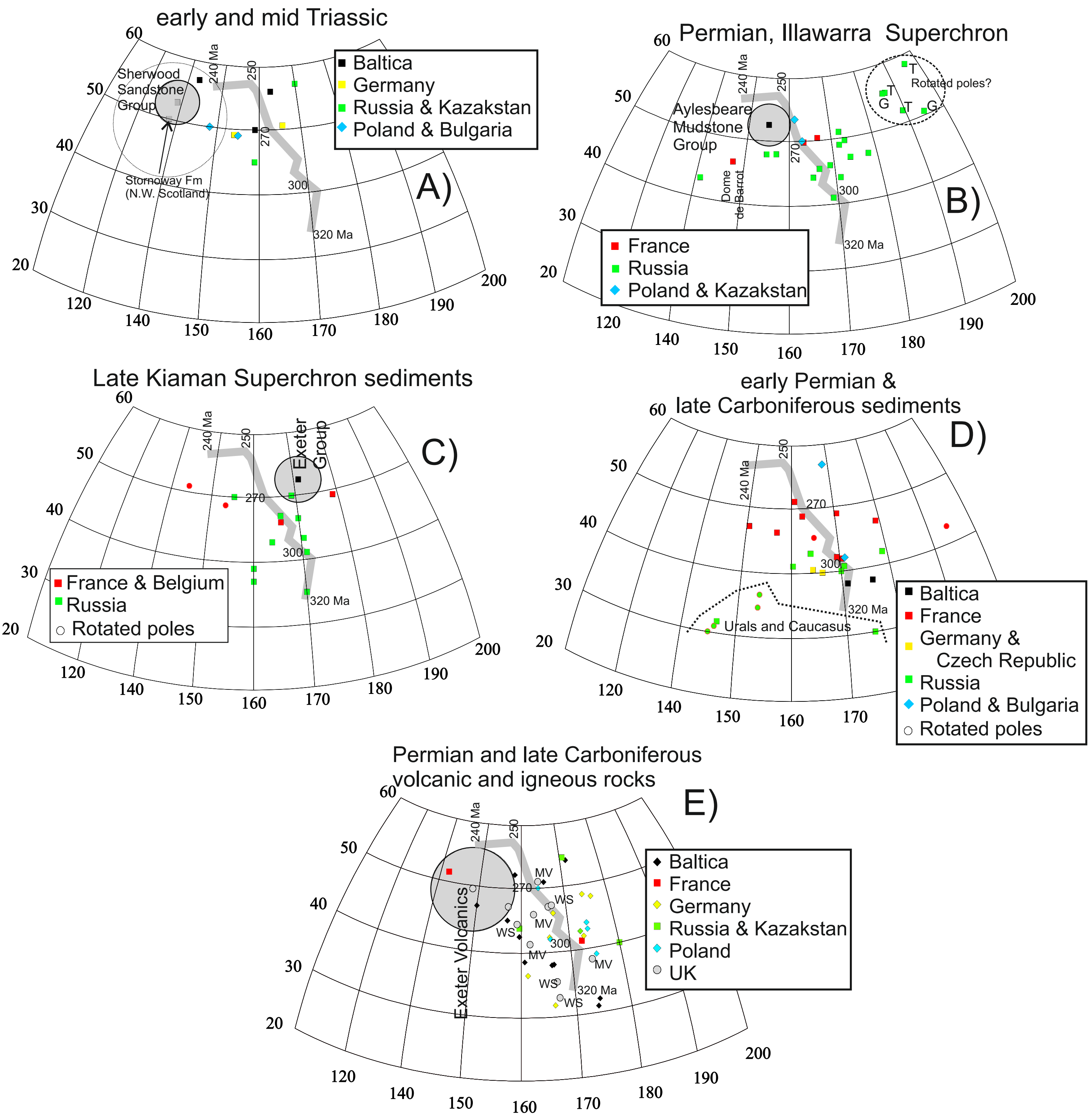


Fig. s7. Stable-Europe virtual geomagnetic poles (VGP) and their comparison to the VGP data from the latest Carboniferous, Permian and early-mid Triassic of the UK. Confidence cones for the units in SW England shown in grey, no confidence cones shown for other data. Each of the plots (A to E) shows the average European VGP path from Torsvik & Cocks (2005) labelled in Ma increments. (A) Lower and Middle Triassic sedimentary units, with Sherwood Sandstone Fm pole from Hounslow & McIntosh (2003), B) Permian sedimentary VGP data younger than the end of the KRPS (i.e. mid-late Wordian and younger). T=data from Taylor *et al.* (2009), G=from Gialanella *et al.* (1997). C) Sedimentary VGP data near the end of the KRPS. D) Lower Permian and latest Carboniferous sedimentary poles. E) Permian and latest Carboniferous volcanic and igneous-based VGP poles. MV=igneous units from the Scottish Midland Valley, WS= Whin sill data (from Liss *et al.* 2004). Data mostly from the Global Palaeomagnetic Database (http://www.ngu.no/dragon/), with newer data from Burov *et al.* (1998), Chen *et al.* (2006), Diego-Orozco *et al.* (2002), Nawrocki *et al.* (2008) and Bazhenov *et al.* (2008). In C) and D) rotated poles are filled circles.

Discussion of VGP data in Figure s7

Creer (1957), Zijderveld (1967) and Cornwall (1967) presented palaeomagnetic data for the Exeter Volcanic Rocks, around Exeter and further north in the Crediton Trough. Cornwall (1967) also performed reconnaissance sampling of the successions in this study, and from the underlying Torbay Breccia Fm. Whilst Zijderveld and Cornwall did use AF demagnetisation, and Cornwall in addition used thermal demagnetisation, relatively few of the sites measured by Cornwall (1967) had structural corrections, whereas the mean direction determined by Zijderveld utilised tilt corrections (Table 1). Cornwall's (1967) mean direction for the Exeter Volcanic Rocks has overly shallows inclination due to inclusion of some southerly-directed magnetisations with positive inclinations, probably due to incomplete demagnetisation of the specimens. The mean VGP pole of Zijderveld (1967) falls towards the end of the late Carboniferous to Permian European APWP path (Fig. s7e), which corresponds well to the range of VGP's from other late Carboniferous to Lower Permian volcanic and igneous units (Fig. S7e).

The sites from the Teignmouth Breccia and from Watcombe Cove have a significant number of specimens having declinations east of south (Table 1; Fig. 9a). The result of this is a more southerly mean, which does however, reflect new data acquired from the Russian Platform by Taylor *et al.* (2009) and Gialanella *et al.* (1997), which are clearly separated (Fig. s7b) from the bulk of previous Russian data obtained from successions younger than the Kiaman Superchron (i.e. Molostovsky 1983; Burov *et al.* 1998). Bazhenov *et al.* (2008) have discussed the problems of this new data as either due to mis-orientation, or vertical axis rotations, hitherto undetected in the eastern part of the Russian platform. Vertical axis rotations of up to 30° have also been inferred for Lower Permian sediments (Fig. s7c) in basins in France and Germany (Diego-Orozco *et al.* 2002; Chen *et al.* 2006), where there are clearer, strike-slip-related tectonic mechanisms to produce this. There are insufficient data in this study to attempt an answer to this for the UK successions, but the similarity in age and tectonic setting of these European basins, south of the Variscan Front infers a common geological or geomagnetic origin for these outlier VGP directions, warranting further investigation, beyond the scope of this study.

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