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Shipboard measurements of sediment stability using a small annular flume—Core Mini Flume (CMF)

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Abstract

Estimates of bed stability in coastal environments are essential to physical, biological, and chemical investigations of cohesive sediments. The Core Mini Flume (CMF), a 200 mm diameter annular flume has been designed to undertake sediment stability experiments on collected intact sediment box cores. Bed properties were assessed for replicate box cores at 3 contrasting sites in UK coastal waters (Tyne [in 2011 and 2012], Plymouth and Celtic Deep), each covering a maximum area of 80 m^2. No significant horizontal spatial variations were found for grain size, bulk density, porosity, or oxygen penetration at the sites. Resuspension experiments performed on replicate cores yielded highly replicable results for each site, giving average erosion thresholds of 0.33 ± 0.02 (Tyne 2011), 0.215 ± 0.03 (Tyne 2012), 0.23 ± 0.01 (Plymouth), and 0.09 ± 0.006 (Celtic Deep) Pa and erosion depths of 10.7 ± 1.7, 6.63 ± 1.10, 3.65 ± 0.95, and 4.6 ± 0.5 mm. Using an already established methodology, the CMF allowed detailed replicate experiments to be performed on-board ship rapidly after sediment collection, while minimizing the time spent at each station. The use of intact box cores minimized the disturbance to the bed often associated with recovering material to a laboratory or remoulding a bed. We have demonstrated that the convenience of laboratory-based methodologies can be combined with the benefit of prompt investigations on undisturbed beds complete with overlying in situ water to produce robust measurements of sediment stability.

Assessing sediment properties, stability, and resuspension dynamics is essential to understanding sediment transport processes, nutrient and chemical fluxes across the sediment-water interface, and biological influences on the seabed. Annular flumes have been successfully used to do this in situ in lakes (e.g., Droppo and Amos 2001; Amos et al. 2003), on exposed intertidal areas (e.g., Tolhurst et al. 2000a; Amos et al. 2004; J. Widdows et al. 2007), in coastal settings (e.g., Amos et al. 1992a, 1992b; Sutherland et al. 1998a; Moreau et al. 2006), and in shelf seas (Thompson et al. 2011; Couceiro et al. 2013); and with material recovered to the laboratory (e.g., Widdows et al. 2002; Bale et al. 2006). The working channel geometry of annular flumes ensures that the applied bed shear stress will be horizontal in nature, more closely replicating natural conditions than the alternative erosion chamber style devices (Thomsen and Gust 2000; Tolhurst et al. 2000a, 2000b; Black et al. 2003; Kalnejais et al. 2007, 2010) or Cohesive Strength Meters (Tolhurst et al. 2000a, 2000b; Defew et al. 2002), which are often used to measure sediment stability in the field and on recovered cores.

However, use of in situ flumes in fully submerged areas usually requires extended periods on-station (e.g., sea carousel, 2+ h (Amos et al. 1992b); Voyager II, 1.5+ h (Thompson et al. 2011), which often results in few stations overall. Smaller in situ devices designed for intertidal work are usually more mobile, but often have reduced overlying water volumes (e.g., Bale et al.'s [2006] PML MAF with a volume of 2.9 L), which limits the potential for collection of water samples for the assessment of suspended particulates, biological, nutrient, or chemical investigations and increases the likelihood of changes to fluid viscosity and particle dynamics due to extreme sediment concentrations during high erosion events. Those with larger volumes usually also have a larger footprint limiting deployment options (e.g., 300 mm diameter Mini-flume [Moreau et al. 2006]). Collection of sediment to be

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transferred to the lab often results in disturbance to the structure and surface of the sediment, which is usually artificially manipulated or remolded before experimentation (e.g., Zimmer et al. 2008). This can affect how comparable the measurements are to those made in situ (Tolhurst et al. 2000a).

The Core Mini Flume (CMF) has been designed to address a number of these issues. Built specifically to fit within a standard 300 mm (or larger) circular box core barrel, such as the NIOZ (HAJA) corer, it allows sediment stability and resuspension experiments to be undertaken on intact sediment cores rapidly after collection. While small enough to fit into the core barrel, the volume (4.7 L) is sufficiently large to allow the removal of 0.5 L water samples without affecting the functioning of the flume. Multiple cores can be taken quickly when on station, to be stored on-ship for processing during transit or the undertaking of alternative ship operations, optimizing ship time and cost while increasing sample numbers to the limit of the available core barrels. A strategy of this kind also allows for greater flexibility of analysis, as time constraints during the experiments are smaller.

Box cores taken in this way are largely undisturbed (Collinson and Thompson 1989), retaining overlying bottom water and in situ biota. Retaining the sediment material in the box core provides an ideal compromise between in situ experimentation and storage, transportation, or remolding of sediment samples in the laboratory.

This article introduces the Core Mini Flume (CMF) and describes the methods used to measure sediment stability. It investigates the replicability and consistency of results from replicate box cores and compares its use on a range of sediment types at different coastal sites.

Materials and procedures

Flume construction and placement

The CMF (Fig. 1a) is a small annular flume based on the design of the Mini Flume (Amos et al. 2000; Thompson and Amos 2002, 2004; Thompson et al. 2004; Widdows et al. 2007; Couceiro et al. 2013). It consists of two acrylic tubes 200 mm and 110 mm in diameter that form a measurement channel 40 mm wide. The outer tube of the flume is initially placed into the sediment (Fig. 1b,c), away from the edges of the core barrel, which may have been disturbed during core insertion. A plastic baffle is fitted 20 mm above the base on the outside the flume to act as an insertion guide. This ensures consistent, flat placement of the flume into the bed while preventing it from sinking into the sediment under its own weight. The smaller

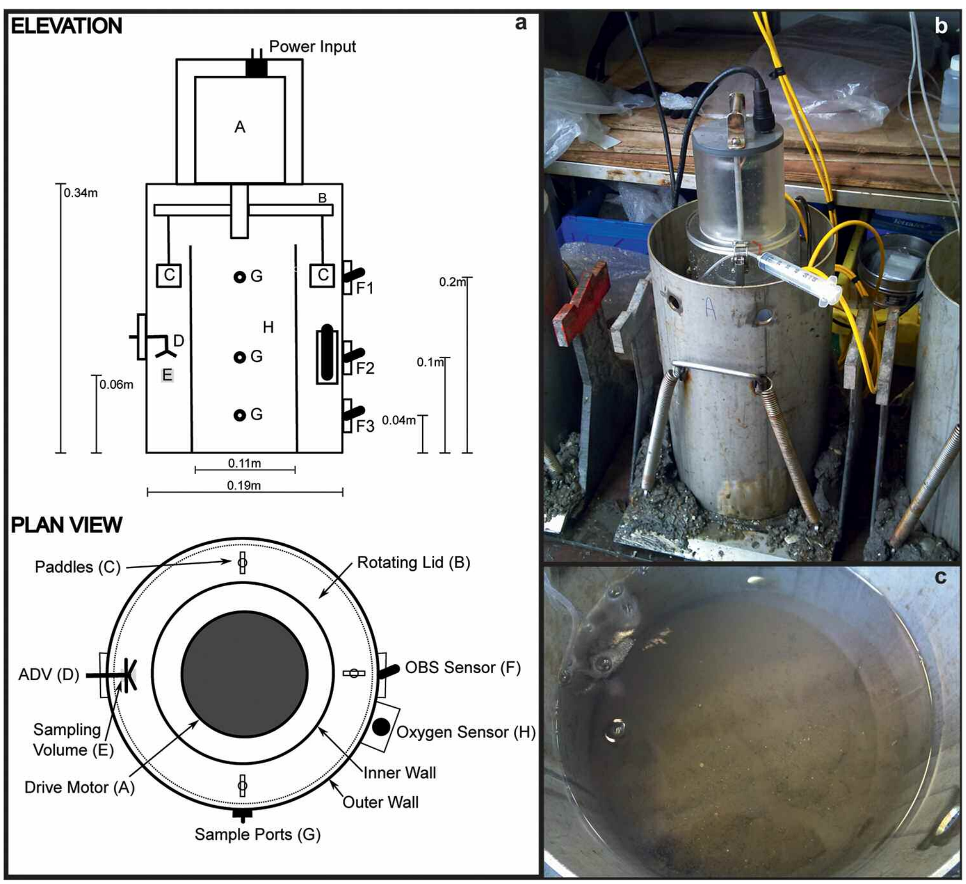

Fig. 1. (a) Schematic of 'CMF' with dimensions. (b) Flume in position in a core barrel. Note the syringe positioned for water sampling. (c) The core surface before flume insertion.

inner tube is pushed into the sediment using a guide built into the flume lid to help align the correct position ensuring the walls of the two tubes are parallel. Once in place on the sediment bed, the flume can be topped up with bottom water collected on site if necessary to a depth of 30 cm, by gently pouring onto a shaped section of clean, plastic "bubble wrap", which prevents bed disturbance during the filling process (Widdows et al. 2007). The lid containing the drive motor and paddle arrangement is then fitted and secured in place.

Current generation and measurement

Four 2.5 cm square equidistantly spaced paddles generate a current. Paddle speed is controlled by a digital stepping motor (Intelligent Motion Systems, Inc.) commanded by a computer through a RS232 serial link. An ASCII script file or direct operator input regulates motor settings and paddle speed, making speed control either automated or real-time as required.

If space within the core barrel allows or if the flume protrudes out of the core barrel, a Nortek Vectrino 'side looking' Acoustic Doppler Velocimeter (ADV) can be fitted looking downwards to measure three components of flow velocity (u = azimuthal, v = radial, and w = vertical) at a height of 6 cm above the bed. The flume speed controller has been calibrated to the ADV: U_6 (m/s) = $3.7 \times 10^{-5}(M) + 0.004$; $R^2 = 0.96$ where U_6 is the azimuthal velocity 60 mm above the bed, and M is a unitless programmable speed value. For comparisons to other systems, these velocities can be converted into bed shear stresses by application of a power law $u_* = 0.121(5_{50}/z)^{1/7}U_z$ (Soulsby 1997), and $\tau_0 = \rho u_*^2$.

Flume Reynolds numbers can be calculated from the expression

$$\mathrm{Re} = \frac{\rho \bar{U} D_h}{\mu} \qquad (1)$$

where the fluid density ρ is 1026 kg m^{-3}, the dynamic viscosity μ is 0.0013 kg m^{-1}s^{-1} (for 10°C) and the flume hydraulic diameter D_h is 80 mm (D_h = 4A/P, where A is the cross section area and P is the wetted perimeter). For the range 0.1 < $_{\text{[insert graphic]}}$ < 1 ms^{-1}, the eroding flows are fully turbulent as $6.3 \times 10^3 < \mathrm{Re} < 6.3 \times 10^4$ (Holland 1970). Under smooth bed conditions, the flow therefore becomes transitional at a flow velocity of 0.04 ms^{-1} and turbulent at 0.06 ms^{-1}.

Suspended sediment measurement

The flume is equipped with three (D&A Instruments) optical backscatter sensors (OBS-1B) at heights of 40, 100, and 200 mm above the base, and equivalently placed plastic water sampling ports allow accurate calibration of suspended particulate matter and the collection of water samples for nutrient or other analysis. The OBS are logged to a Campbell Scientific USA CR10 data logger at a maximum rate of 4 Hz.

Oxygen measurement

An Aanderaa Data Instruments (AADI) oxygen optode is located at the same height as the middle OBS (100 mm above the base) to allow time series of water oxygen concentration to be taken.

Bed sampling

Four intact cores were collected from the Centre for Environment, Fisheries and Aquaculture Science research vessel *Cefas Endeavour* (cruise no: CEND 5_11) using a 300 mm diameter NIOZ (HAJA) corer, from 44 m of water ~ 11 km east of the Tyne (54°58.44 N, 1°15.349 W) in February 2011 to test the flume, and a further three were used to assess local sediment heterogeneity. In January 2012, additional cores were taken (CEND 1_12) using the same system from sites Tyne (4 intact cores, 50 m water depth, 54° 58.58 N, 01° 15.479 W), Plymouth (3 cores, 14m water depth, 50° 20.875 N, 04° 07.944 W), and Celtic Deep (3 cores, 130m water depth, 51° 15.999 N, 06° 28.991 W) to assess the flumes use on a range of different bed types (Fig. 2). Dynamic positioning was used during operations to minimize the distance between successive cores. The core shoes were covered with a layer of neoprene approximately 10 mm thick, which provided a compressible surface that the core barrel could form a seal with. This, along with the muddy component of the sediment allowed a seal sufficient to maintain a head of water for the resuspension experiments. One core from each site was subsampled immediately after collection by taking two 100 mm diameter push cores and one 60 mL syringe core from the core center, away from the barrel sides. One of the 100 mm cores was immediately used for vertical oxygen profiling following the methodology of Sapp et al. (2010), and the other was refrigerated for subsequent particle size analysis (*see* "Bed characterization"). The 60 mL syringe core was frozen for subsequent organic carbon content and bulk density investigations (*see* "Bed characterization"). Bottom water was collected at each site using Niskin bottles attached to the Cefas CTD rosette. This was used to top up the box cores if necessary to provide sufficient water depth for the resuspension experiments.

The retrieved box cores (four each from Tyne and Tyne 2, three each from Plymouth and Celtic Deep) were left for 24 hours after collection at ambient air temperature (~8°C) to enable pore water profile measurements of nutrient diffusive fluxes to be made using gel diffusive equilibrium thin-film (DET) probes (*see* "Nutrient sampling"). Air stones were kept in the overlying water during this time to prevent anoxia. This also allows any material potentially resuspended by the coring process to settle on a scale similar to in situ resuspension events (Thompson et al. 2011). Only cores with minimal visible burrows or macrofauna were retained for the resuspension experiments, as these would affect the ability of the flume to seal with the sediment and hold an appropriate head of water. The cores then underwent the primary resuspension experiments (see resuspension experiments). After the resuspension experiments were completed, additional 100 mm push cores and 60 mL syringe cores were taken from the central, undisturbed portion of the core. This was done post-resuspension to ensure an undisturbed bed was maintained for the experiments, to assess any inter-core differences in sediment properties.

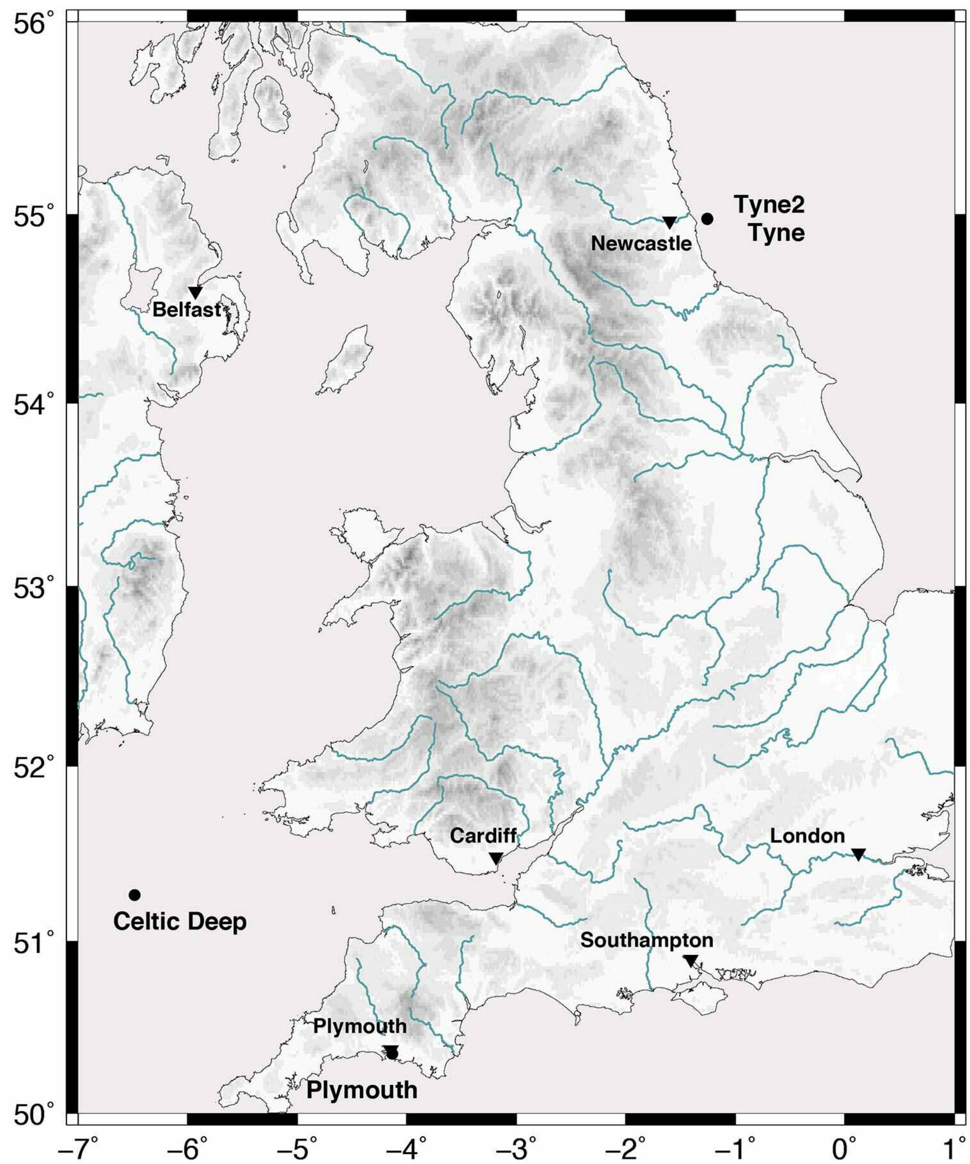

Fig. 2. Location map of the four sites visited. Tyne 2011 as part of Cefas research cruise CEND 5_11 in Feb 2011 and Tyne 2012, Plymouth, and Celtic Deep as part of Cefas research cruise CEND 1_12 in January 2012. Tyne 2011 and Tyne 2012 are located approximately 400 m from each other, and so are represented by a single point.

Bed characterization

The 100 mm core subsamples were extruded and the top 30 mm subdivided into 10 mm sections. Particle size analysis was undertaken using a combination of dry sieving (>63 μm) to quarter-phi resolution and laser sizing (<63 μm) using a Coulter LS130 laser sizer. Classifications are made following geometric (modified) Folk and Ward (1957) graphical methods in μm, except mean grain size that was determined using the arithmetic method of moments (Blott and Pye 2001).

The 60 mL syringe cores were defrosted slowly at 5°C in an upright position to maintain internal structure. The defrosted sediment was extruded and sub-sectioned into known volumes representative of a depth of 10 mm (for the top 30 mm) or 20 mm depth (for the remainder). The samples were dried overnight at 50°C and wet bulk density (ρ_b) and water content were calculated. The sediment porosity (φ) was calculated according to Burdige (2006);

$$\rho_b = \varphi\rho_w + (1 - \varphi)\rho_s \quad (2)$$

where ρ_b and ρ_w are the densities of the sediment grains and water, respectively.

Organic carbon content (%) was determined from the bulk density sub-samples following drying at 50°C, by loss on ignition (550°C, 5.5 h, Grabowski et al. 2011).

Resuspension experiments

After insertion of the CMF into an intact core, the water level was topped up to 0.30 m with collected bottom water where necessary and the flume left for 10 min for the sensors to stabilize and record background measurements. To design the velocity regime, a single core from each site was used as a 'test' core (Core T) for high-resolution measurements of sediment stability. A stepwise increasing velocity regime (velocities ranging from 0.02–0.56 ms^{-1} in steps of 0.02 to 0.04 ms^{-1}) was applied to the sediment in the manner followed by Amos et al. (1992a, 2003, 2004), Sutherland et al. (1998a, 1998b), and Thompson et al. (2011). This allowed for the accurate planning of speeds to be programmed for the remaining experiments, therefore allowing automation of the applied velocity regime and timings, and ultimately better replicability. Ten-minute time steps were used for the test cores, while 20-minute time steps were used for all other cores.

OBS data were calibrated against suspended particulate matter concentration (S, gL^{-1}) using 50 mL water samples taken from the middle sampling port at the initiation of each velocity step, or every 3 or 4 velocity steps dependent on the velocity regime, and filtered through a 47 mm GF/F filter (Whatman). The S time series was time averaged over 20 s to eliminate high frequency, short-term variability in the record (following the methodology of Widdows et al. 2007) and normalized to a starting concentration of zero for easier inter-experiment comparison.

Erosion rates (E, k $gm^{-2}s^{-1}$) and equivalent depths of erosion (z_e, mm) were calculated following the procedures outlined in Thompson et al. (2011) where

$$E = \frac{\delta M}{\delta t} = \frac{V(S_{end} - S_{start})}{\Delta t A} \quad (3)$$

$$\frac{dz_e}{dt} = \frac{dM}{dt}\frac{1}{A\rho_b} \quad (4)$$

where M is the eroded dry mass of sediment (kg), V is the volume of the CMF (m^3), A?is the flume bed area (m^2), and Δt is the duration (s) of the applied eroding bed stress.

Critical erosion thresholds were defined as the point of initial erosion of the bed, the velocity where the suspended sediment concentration deviates from ambient conditions in the flume. This is determined from a regression line of the 20 s averaged suspended particulate matter (S) versus flow velocity (U_6) (full details can be found in Sutherland et al. 1998b; Amos et al. 2003; Widdows et al. 2007), which has been found accurate even in cohesive sediments with high proportions of fine sands (Sutherland et al. 1998b).

Nutrient sampling

The CMF was designed with nutrient sampling and nutrient flux measurements in mind (Couceiro et al. 2013). Immediately after sediment core collection DET (diffusive equilibrium in thin films) probes (Davison et al. 2000; Monbet et al. 2008) were deployed for 24 hours around the outer edge of the core barrel to enable fine resolution pore water profiles of nitrate, nitrite, ammonium, phosphate, and dissolved silicon to be determined. The DET probes disturb the sediment during insertion and removal and so were placed outside the bed area the flume would subsequently occupy.

During the resuspension experiments, 0.195 L overlying water was removed for OBS calibration and concurrent nutrient analysis, well below the maximum water removal limit. Water samples for nitrate, nitrite, ammonium, phosphate, and dissolved silicon were taken at the initiation of each velocity step (t = 0), and then after 1, 5, and 10 min. In total, 25 measurements of each were taken during every resuspension experiment. Full details of the chemical analysis and results are presented in Couceiro et al. (in prep).

Assessment

Bed characterization

To assess the consistency of the results from the CMF, it was important to first establish the natural variability in sediment properties, including both intra- and inter-core variability. Grain size distributions for the top three centimeters of cores from each of the four sites are shown in Fig. 3, whereas a summary of the main statistics is given in Table 1. All samples are classified as poorly or very poorly sorted muddy sands or sandy muds. Skewness ranges from coarse skewed (Celtic Deep), through symmetrical (Tyne 2011) to fine and very fine skewed (Tyne 2012 and Plymouth, respectively). The samples were leptokurtic at the two Tyne sites, mesokurtic at Plymouth and ranging from Leptokurtic at the surface to platykurtic at 3cm depth for Celtic Deep. Significant differences in grain size distribution were found with depth (Chi-squared, $P < 0.05$), and between all sites (one-way ANOVA, $P < 0.001$), but not between replicate cores taken at the same site (e.g., Tyne, 2011: one-way ANOVA, $P = 0.564$).

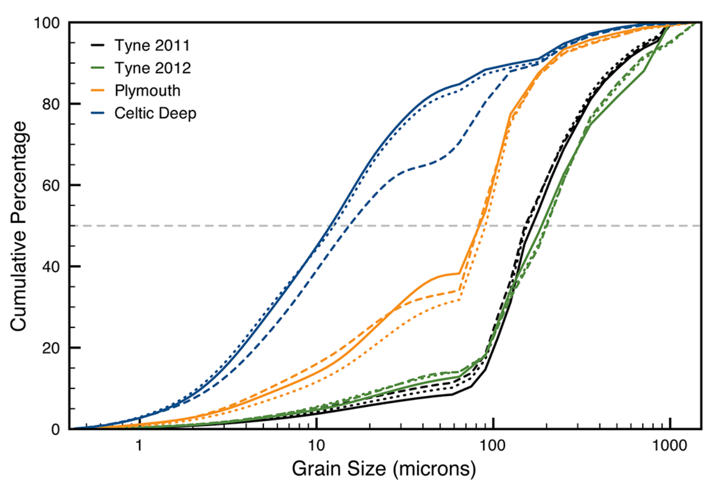

Fig. 3. Particle size (cumulative distribution curves) for the top 3 cm of subsampled cores. Solid line represents top 1 cm, dotted line 1-2 cm, dashed line 2-3 cm.

Table 1. Grain size statistics (median [d50], mean, sorting, skewness, and kurtosis in μm), for the top three centimeters each core. Where multiple cores were available from a site, standard deviations are presented in brackets.

D_{50}	0–1 cm	1–2 cm	2–3 cm
Tyne (2011)	195.8 (± 5.2)	184.7 (± 4.7)	182.5 (± 3.7)
Tyne (2012)	261.2	276.6	280.3
Plymouth	116.0	124.1	114.9
Celtic Deep	13.1	13.7	16.8
Mean			
Tyne (2011)	240.6 (± 9.6)	235.7 (± 4.0)	226.0 (± 10.8)
Tyne (2012)	284.8	274.3	273.1
Plymouth	70.3	78.4	66.1
Celtic Deep	14.0	16.3	21.6
Sorting			
Tyne (2011)	1.4(± 0.08)	1.4(± 0.09)	1.5(± 0.04)
Tyne (2012)	3.320	3.413	3.344
Plymouth	4.221	3.983	4.630
Celtic Deep	4.689	5.416	5.688
Skewness			
Tyne (2011)	0.03(± 0.02)	0.04(± 0.02)	0.03(± 0.05)
Tyne (2012)	–0.103	–0.182	–0.197
Plymouth	–0.490	–0.482	–0.475
Celtic Deep	0.144	0.176	0.182
Kurtosis			
Tyne (2011)	1.7(± 0.04)	1.7(± 0.07)	1.7(± 0.10)
Tyne (2012)	1.541	1.705	1.717
Plymouth	1.00	1.140	0.999
Celtic Deep	1.215	1.164	0.803

Dry bulk density, porosity, and organic carbon content for all four sites are shown in Fig. 4. Overall, bulk density (Fig. 4a) appears to increase with depth in the top 4 cm at all sites, and then remains largely constant. However, one-way ANOVA tests of variation with depth showed no significant change in the first 3 cm at any site, and below this depth only at the Tyne in 2011. The depth averaged (3 cm) bulk densities between the sites were found to be significantly different (One-way ANOVA, $P < 0.05$), except between Tyne 2011 and Plymouth (Tyne 2011: 1068, Tyne 2012: 1308, Plymouth: 1140, Celtic Deep: 688 kg/m^3). Porosity (Fig. 4b) appears to decrease over the initial 4 cm, before remaining constant in a similar way to the related bulk density. Organic carbon (Fig. 4c) shows a considerable amount of scatter between 1 and 12%, but no significant change with depth (one-way ANOVA, $P = 0.44$), between replicates (Friedman's two-way analysis, $P > 0.186$) or between sites (Friedman's two-way analysis plus Wilcoxon signed-rank post-hoc test with Bonferrion adjustment, $P > 0.008$).

Oxygen penetration depths taken from all sites are presented in Table 2. The difference in depth between the measurements is not significant (ANOVA, $F_{2,2} = 2.57$, $P = 0.28$) and so the average depths are used.

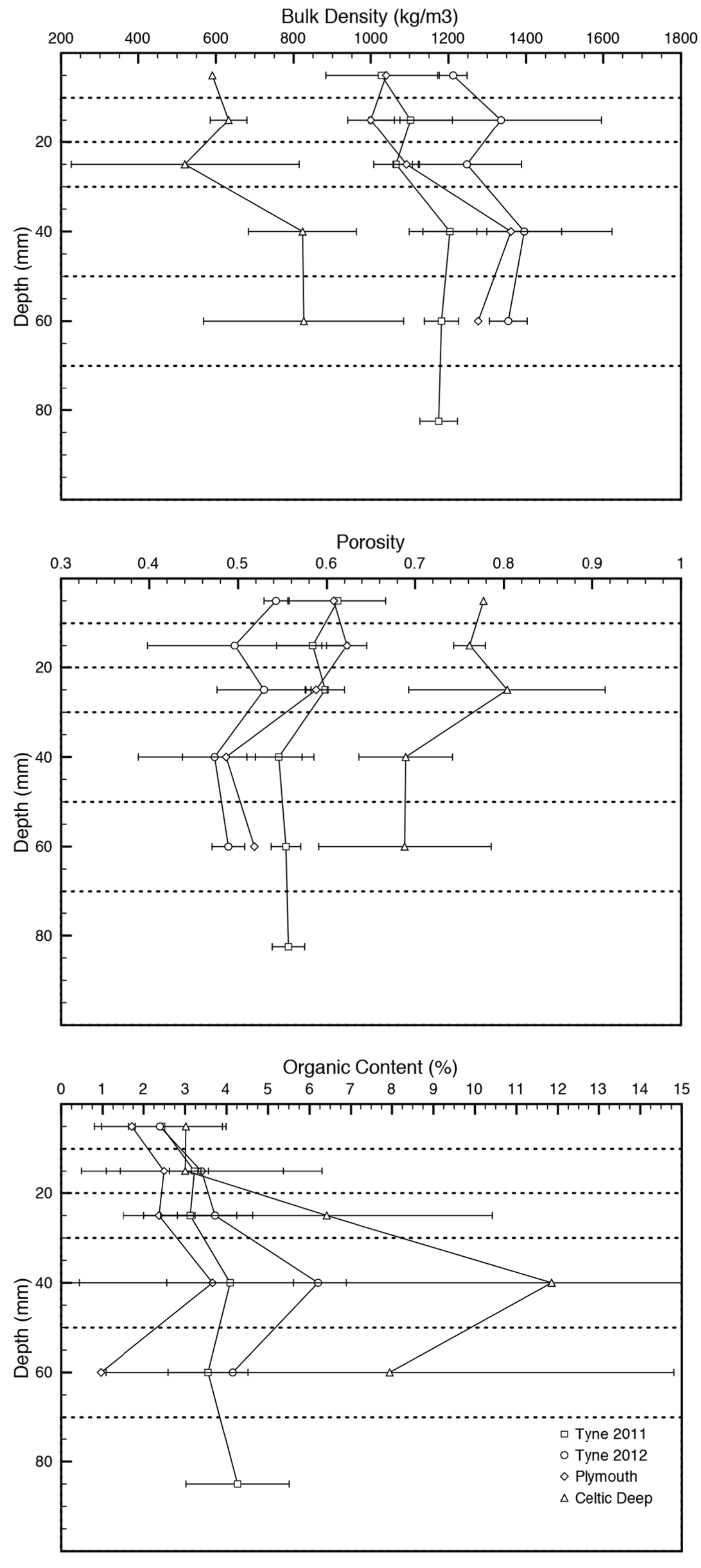

Fig. 4. (A) Dry bulk density, $n = 3$, (B) porosity, $n = 3$, (C) organic carbon content, $n = 3$. All parameters plotted against depth. Figures show averaged values at each depth, with error bars representing standard deviation. Dashed horizontal lines illustrate the vertical distance the each measurement represents.

Table 2. Thresholds of erosion, depth of erosion, and oxygen penetration depths for all sites.

Site	Core	Critical erosion threshold U_6 (m/s)	Critical erosion threshold (Pa)	Depth of erosion (mm)	Oxygen penetration depth (mm)
Tyne (2011)	B	0.197	0.32	5.5	10.7 ± 1.7
	C	0.193	0.31	4.8	
	T (High Resolution)	0.206	0.35	6.0	
Tyne (2012)	A	0.165	0.23	3.0	6.63 ± 1.10
	B	0.166	0.23	1.7	
	C	0.145	0.17	1.1	
	T	0.167	0.23	2.1	
Plymouth (2012)	A	0.163	0.22	5.4	3.65 ± 0.95
	B	0.169	0.24	4.6	
	T	0.168	0.23	4.4	
Celtic Dee*p* (2012)	A	0.126	0.09	12.5	4.6 ± 0.5
	B	0.129	0.10	12.0	
	T	0.123	0.09	12.6	

The replicate cores can therefore be considered sufficiently similar to be treated as the same bed type for each experiment, but the four sites are sufficiently different in terms of grain size and bulk density to be considered distinct bed types.

Resuspension experiments

Fig. 5 shows the time series of S (A), erosion rate (B), and eroded depth (C) for cores at each site (Tyne, 2011 [1], Tyne, 2012 [2], Plymouth [3], Celtic Deep [4]). Fig. 5A1 (Tyne) shows S increasing for each velocity step, initially in a way typical of type 1b erosion (an increase in S decaying asymptotically with time) and in the final step exhibiting type 2 erosion (S increasing linearly with time; Parchure and Mehta 1986; Amos et al. 1992a, 1997). Tyne is the only site that experiences this change in erosion type, with the others exhibiting only type 1 erosion. At each site, the replicate cores behave in generally the same way, with broadly similar levels of S at each of the lower velocity steps for the replicates but increasing disparity at higher velocities. The large discrepancy with Tyne 2011, core A is the result of a leak beginning after the first three velocity steps, resulting in the water level falling in relation to the driving paddles and preventing the flume from achieving the programmed velocity. Therefore, only the initial results of this replicate will be considered. Maximum differences in S of 12 g/L (Tyne 2011), 10 g/L (Tyne 2012), 6 g/L (Plymouth), and 2 g/L (Celtic Deep) are found by the end of the experiments. Celtic Deep, which had the lowest bulk density, had the highest final S of all the sites (31.06 g/L on average). Tyne 2012 had the highest bulk density and the smallest final S (13.77 g/L), with Tyne 2011 and Plymouth having broadly similar values (23.45 and 22.01 g/L respectively). Fig. 5B (1-4) show peaks in erosion rate evident at the beginning of each of the early velocity steps (typical of type 1b erosion), being more constant during the last step of the Tyne 2011 experiments (more indicative of type 2 erosion). However, the height and width of these erosion peaks varies, with Celtic Deep exhibiting the widest, lowest peaks indicative of more sustained erosion rates throughout each velocity step.

Fig. 5C(1-4) shows the equivalent eroded depths for each of the replicates, along with oxygen penetration depths. Maximum eroded depths were ~ 5.4, 1.5, 3.7, and 12.8 mm for Tyne, Tyne 2, Plymouth, and Celtic Deep, respectively, corresponding to the total S values. The equivalent eroded depth only indicates the amount of material removed from the bed and into resuspension, which in this case is above the anoxic zone at Tyne, but below it at Plymouth and Celtic Deep (Table 2, and Couceiro et al. 2013; in prep). However, any component moving in the bedload is not included in this measurement, meaning that the depth of re-working may be significantly deeper.

Critical erosion thresholds are given in Table 2, with an example shown in Fig. 6. A very high level of similarity is seen between the replicate values at each site, with average critical erosion thresholds (U_{6cr}) of 0.20 (± 0.007), 0.16 (± 0.01), 0.17 (± 0.003), and 0.13 (± 0.003) $ms^{-1}$for Tyne 2011 and 2012, Plymouth and Celtic Deep, respectively, equivalent to bed shears stresses of 0.09–0.35 Pa. These values also compare well to previous studies that have used in situ annular flumes on sediments with similar bulk densities (0.02–0.5 Pa: Amos et al. 1997, 1998, 2003; Moreau et al. 2006; Sutherland et al. 1998b).

Spatial variation

Variation in soft sediments exists at a range of special scales from large-scale variation related to factors such as water depth and sediment types, to 'within-location' variations at the sub-meter scale (Morrisey et al. 1992). Field studies have shown significant cm-m scale horizontal variations within estuarine and coastal depositional environments (Grabowski et al. 2011), related to combinations of the physical composition of the material (e.g., size, bulk density, etc.), biological factors (e.g., bioturbation, biostabilization, microbial communities, etc.), and geochemical properties (such as clay mineral-

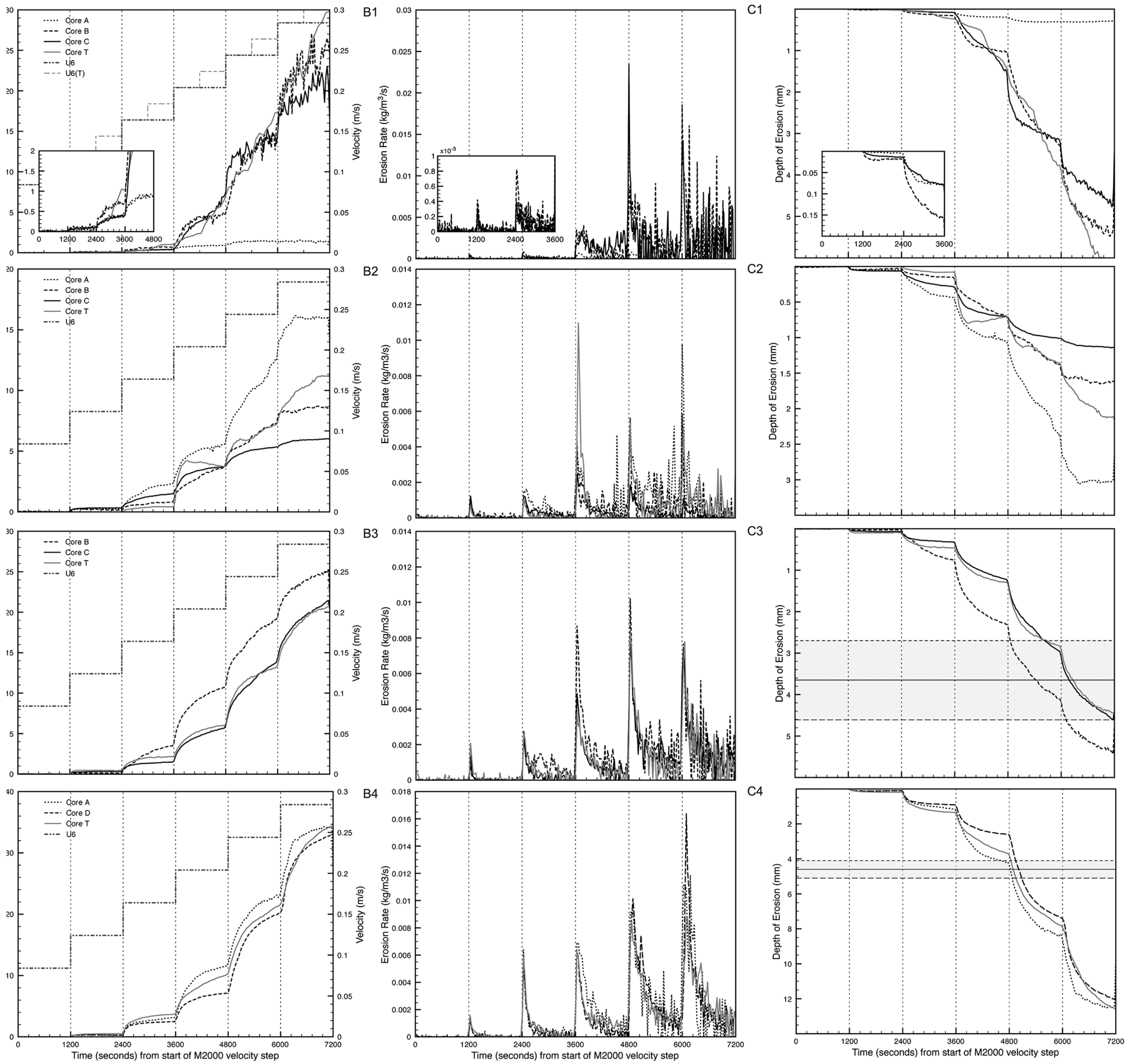

Fig. 5. Time series of (1) suspended particulate matter (S), (2) erosion rate, and (3) depth of erosion for (A) Tyne 2011, (B) Tyne 2012, (C) Plymouth, and (D) Celtic Deep. Insets provide a more detailed view of initial velocity steps. Velocity steps (U6) last 1200 s, with change of velocity denoted by dashed vertical lines. Note the difference in resolution in velocity steps for A (1-3), Core T where each velocity step lasts 600 s: U6(T), but the velocity change over the entire time period is equal. Oxygen penetration depths are plotted alongside depth of erosion where these are eroded, as a band representing 1 standard deviation around the mean.

ogy, organic content, etc. [Grabowski et al. 2011]). The high level of similarity between replicate core comparisons of the sediment properties at each site suggests that the scale of variability is larger than that of either an individual core (300 mm), or the sampling area as a whole (~80m^2). The scale of each resuspension experiment is equal to the diameter of the flume (i.e., 200 mm) and averaged over the area of the flume bed, so finer scale patchiness is not represented by the resuspension experiments.

One of the largest variabilities in sediments tends to be in

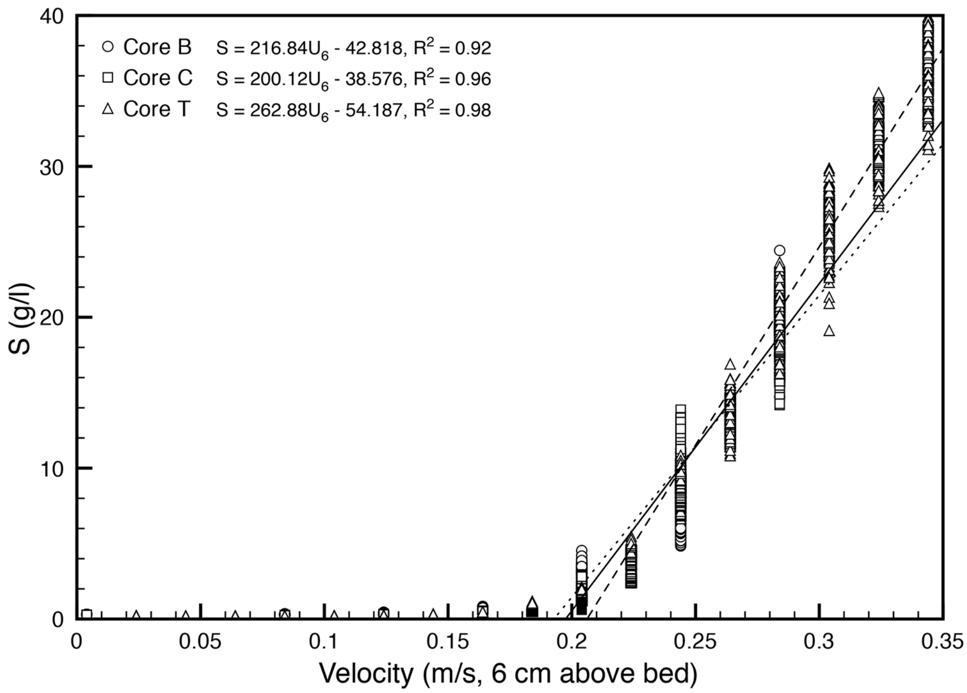

Fig. 6. Suspended particulate matter (S) versus applied velocity for cores B, C, and T, with regression lines used to determine critical erosion thresholds.

Table 3. Principal component analysis results for the four sites. Figures in bold indicate those variables which contribute most strongly to the variance.

	PC1	PC2
D50	0.974	–0.103
Mean grain size	0.975	0.153
Sorting	–0.807	–0.327
Skewness	–0.080	0.993
Kurtosis	–0.767	0.639
Bulk density	0.831	–0.518
% Organics	–0.319	0.918
% Variance	56.27	37.81

the vertical, where erodibility depends on depth (Grabowski et al. 2011). In this case however, there seems to be little significant change in the sediment properties with depth, except grain size and bulk density at Tyne 2011. It is interesting that Tyne 2011 is also the only site to show clear evidence of a change in erosion type during the resuspension experiments. However, it was not possible to resolve the physical parameters of the sediment to the same scale as the depth of erosion (max ~12 mm) due to factors of statistical significance, and the presence of type 1b erosion implies an increase in sediment stability with depth on the sub-millimeter scale.

A principal component analysis of all sites (PCA, Table 3, Fig. 7) shows that 94% of the variance between the sites can be explained by two principal components. PC1 comprises of mostly physical sediment properties (grain size, sorting, and bulk density) whereas PC2 is comprised of physical and geochemical properties (skewness and percentage organics). Multiple linear regression of these characteristics (Table 4) shows significant ($P < 0.05$) relationships between the maximum suspended sediment concentration and grain size (R^2 = –0.899) and bulk density (R^2 = –0.921) and between depth of erosion and bulk density (R^2 = –0.958). This explains the similarities between the values given for Tyne 2011 and Plymouth, which have similar bulk densities. Strong relationships ($P < 0.10$) are also found between eroded depth and median grain size (R^2 = –0.854), critical erosion threshold and sorting (R^2 = –0.883), and eroded depth and critical erosion threshold (R^2 = –0.82).

It is interesting to note that the stability of the sediments, as indicated by their critical erosion threshold, was very replicable for each of the sites, whereas there was more variation in erosion rate, maximum depth of erosion, and the amount of material suspended. This seems to confirm findings of earlier in situ work in the North Sea, which indicated that the critical erosion threshold and subsequent erosion properties may not be controlled by the same processes (Thompson et al. 2011).

Discussion

The Core Mini Flume was successfully used to investigate sediment stability, providing consistent results in replicates over the same bed type and showing variability related to changing sediment properties over a range of muddy bed types. The methodology adopted meant that multiple cores could be taken quickly, and experiments performed while

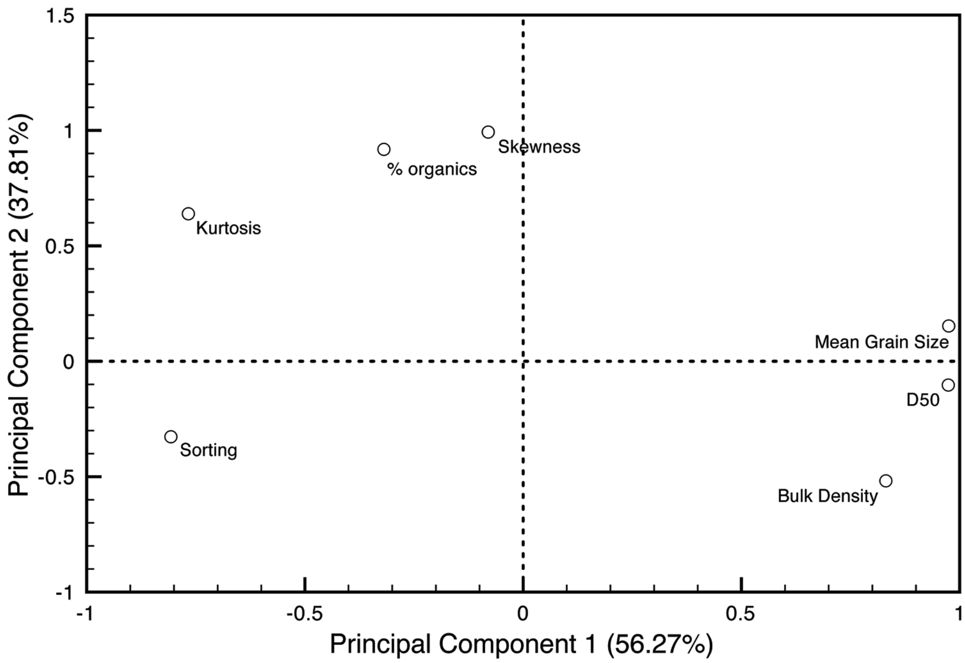

Fig. 7. A principal component analysis of all sites showing that 94% of the variance between the sites explained by two principal components.

Table 4. Correlation matrix (Pearson's linear correlation coefficients) between bed properties and measured erosion characteristics (n = 4), where τ_{cr} is the critical shear stress. From multilinear regression analysis, significance at $P < 0.05$ is indicated by bold text.

	τ_{cr}	S_m	D_{50}	MGS	SOR	SKW	K	ρ_b	%O	Z_e
Maximum SSC (S_m)	–0.396									
Median Grain Size (D50)	0.711	**–0.899**								
Mean Grain Size (MGS)	0.696	–0.795	**0.966**							
Sorting (SOR)	–0.883*	–0.256	–0.653	–0.759						
Skewness (SKW)	–0.262	0.335	–0.165	0.086	–0.220					
Kurtosis (K)	0.565	–0.363	0.670	0.837*	–0.855*	0.569				
Bulk Density (ρb)	0.655	**–0.921**	**0.904**	0.764	–0.401	–0.569	0.295			
% Organics (%O)	–0.533	0.411	–0.358	–0.134	0.074	**0.956**	0.329	–0.692		
Eroded depth (Ze)	–0.820*	0.777	–0.854*	–0.720	0.540	0.611	–0.300	**–0.958**	0.783	
Peak erosion rate (E)	0.375	0.659	–0.265	–0.107	–0.555	0.397	0.317	–0.455	0.232	0.212

*indicates significance at $P < 0.10$.

other ship operations were ongoing. Because the experiments were undertaken on deck, the only limitation was the weather and ability to core. However, a sensible placement of the experimental equipment, i.e., midships, reduced the effect of ship movement during bad weather, preventing excessive on-deck motion of the retained cores and preventing loss of overlying water or bed surface disturbance.

It is important to note that one of the principal controlling factors of the experiments was the ability of the material to hold a head of water. At present this limits the technique to sites with a muddy component and an absence of burrows, but methods could be developed that sealed the bottom of the core barrels, allowing CMF to be used on sandy beds.

The central region inside the flume channel area ensured that an undisturbed section was available for small cores or subsamples to be taken after the resuspension experiments, for assessment of the sediment properties. Results showed that no significant differences were found between these post-resuspension cores and those taken from separate core-barrels. This means that with sufficient care taken during flume removal, the number of cores required can be reduced to the number of replicate resuspension experiments required, while ensuring the sediment properties measured represent the same bed areas experimented on. It also saves time and effort during the coring procedures.

From a nutrient sampling viewpoint, the flume allowed sufficient volume for removal of water samples for five different chemical species at a high enough resolution to see short-term variation in their concentration (Couceiro et al. in prep). Continuous water column oxygen concentrations could be measured, and expansion possibilities exist as additional sensors could be added to the flume as required.

Resuspension experiments run in this way minimized the time required at each site to approximately 1-2 h, compared with the 6-10 h that would have been required for the same experiments to be carried out in situ. If in situ experiments had been undertaken, any pore water profile measurements collected would not have been from the same sediment as the resuspension experiments were performed on.

The surface of the cores was undisturbed by the recovery process (structures were seen intact on the core surface) although it should always be noted that material may be lost during placement of the NIOZ corer as the pressure wave approaches the bed (Jumars 1975a, 1975b). To minimize this loss, the core was lowered very slowly into the bed, but there was no way to make an assessment of this type of disturbance. Once collected, the sediment was retained in the core barrel for the duration of the experiments, and therefore once collected, underwent no further manipulations. The level of disturbance was certainly less than one would expect from recovery or remolding in the laboratory, and had the benefit of retaining the overlying bottom water.

It has been noted that even when using the same measurement device, erosion thresholds and rates can vary due to the handling of the sediment, or operational procedure and calibration approaches (Grabowski et al. 2011). The equipment and methodology described in this article ensure that variations in measured parameters are small as the sediments are handled in a constant way, and the disturbance to the bed structure and sediment surface is minimized (Tolhurst et al. 2000b).

Comments and recommendations

The Core Mini Flume (CMF) was designed for on-ship investigations of bed stability, and sediment resuspension. Made to fit into an intact 300 mm or larger box core barrel, the aim of CMF was to minimize time spent on-site while maintaining an intact bed structure and surface for experimentation. CMF was found to be successful in this regard, removing the need to subsample or remove sediment from the cores, giving consistent results when replicated over a range of cohesive bed types, and was suitable for chemical investigations of nutrient fluxes. Less than 2 h were required at each site to collect sufficient sediment core for 8+ hours of flume experimentation.

Limits to the system relate to the need for the core to maintain a head of water for the duration of the experiments, and a requirement for a flat surface within the core for the flume to sit on. The former is satisfied when working in muddy sediments, but adaptations to the core barrel or shoe may be necessary before using the system in predominantly sandy sediments or those with many burrows.

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