

# The nature and origin of deep ocean clay crust from the Gulf of Guinea

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Deep ocean sediments off the west coast of Africa exhibit a peculiar undrained strength profile in the form of a crust, albeit of exceptionally high water content, overlying normally consolidated clay. Hot-oil pipelines are installed into these crustal sediments, so their origins and characteristics are of great interest to pipeline designers. This paper provides evidence for the presence of burrowing invertebrates in crust material, and for the way sediment properties are modified through their creation of burrows, and through the deposition of faecal pellets. A variety of imaging techniques are used to make these connections, including photography, scanning electron microscopy and X-ray computer tomography. However, the essential investigative technology is simply the wet-sieving of natural cores, which reveals that up to 60% by dry mass of the crustal material can consist of smooth, highly regular, sand-sized capsules that have been identified as the faecal pellets of invertebrates such as polychaetes. Mechanical tests reveal that these pellets are quite robust under effective stresses of the order of 10 kPa, acting like sand grains within a matrix of fines. Their abundance correlates closely with the measured strength of the crust. While this can easily be accepted in the context of a pellet fraction as high as 60%, the question arises how a smaller proportion of pellets, such as 20%, is apparently able to enhance significantly the strength of a sediment that otherwise appears to be normally consolidated. A hypothesis is suggested based on the composition of the matrix of fines around the pellets. These appear to consist of agglomerates of clay platelets, which may be the result of the breakdown of pellets by other organisms. Their continued degradation at depths in excess of 1 m is taken to explain the progressive loss of crustal strength thereafter.

KEYWORDS: clays; fabric/structure of soils; laboratory tests; microscopy; offshore engineering; pipelines

## INTRODUCTION

The sediments found in deepwater oil and gas developments off the west coast of Africa have been of interest to hot-oil pipeline designers for a number of years. Installation of oil flow-lines in these areas causes partial embedment into the shallow sediments, resulting in the need to understand their medium- and long-term behaviour under hot pipeline conditions. Installed pipelines undergo several hundreds of thermal cycles during their operational life, moving many metres during each cycle (Bruton *et al.*, 2007; White & Cheuk, 2008). Pipeline designers therefore require an understanding of the undrained shear strength ( $s_u$ ), which governs the depth of initial pipe embedment, and the axial soil-pipeline coefficient of friction ( $\mu$ ), which governs the ultimate self-weight anchorage along sections of pipeline adjacent to designed-in buckles. The consolidation time that must elapse before the soil resistance to pipeline movement changes from the in situ undrained strength to the fully drained resistance created by the pipeline self-weight is also of interest.

A significant number of in situ undrained shear strength tests have been undertaken in deep ocean sediments using vane shear tests, cone penetration tests (CPTs) and T-bar tests: see Stewart & Randolph (1994) for the test procedure and interpretation. The results of CPT and T-bar testing in West African sediments at water depths ranging between 500 m and 2000 m indicate a 'crust' in the top metre of sediment, within which the clay is an order of magnitude stronger than would be expected for a virgin deposit. Meas-

ured undrained shear strengths typically rise at a rate of about 24 kPa/m up to a maximum of about 14 kPa at 0.5 m to 1 m depth, as shown in Fig. 1. Below the crust, an equally sharp rate of strength reduction is observed. Below 2 m, a strength profile approximating to normally consolidated conditions is then apparent, characteristically demonstrating strength proportional to depth for the succeeding tens or hundreds of metres of apparently similar sediment. The virgin consolidation line for highly plastic clay ( $I_p \approx 1$ ) according to Skempton (1954), and based on a submerged unit weight of 2.5 kN/m<sup>3</sup>, is shown for comparison. The location of the crust at the interface of the sea-bed suggests that it depends on some currently existing transport process. However, the sudden reduction of crust strength following modest sediment burial also suggests vulnerability. Although a significant amount of data is now available highlighting the phenomenon of deep ocean clay crusts, no apparent correlation has previously been found between its presence and the constituents of the sediment determined in situ or in the laboratory (Colliat *et al.*, 2011).

## EVIDENCE FOR BURROWING INVERTEBRATES

An investigation into the origin of crust material is presented in this paper. The investigation was undertaken by analysing natural core samples taken from box-core samples and core samples taken using STACOR technology, described in Borel *et al.* (2002). A range of observational and laboratory methods were used to identify the role of burrowing invertebrates in the transformation of sediment strength.

### Burrows

A box core recovered from 1400 m water depth in the Gulf of Guinea revealed several large, open burrows within the crust material, underlying a soft, red-brown 'ooze'.

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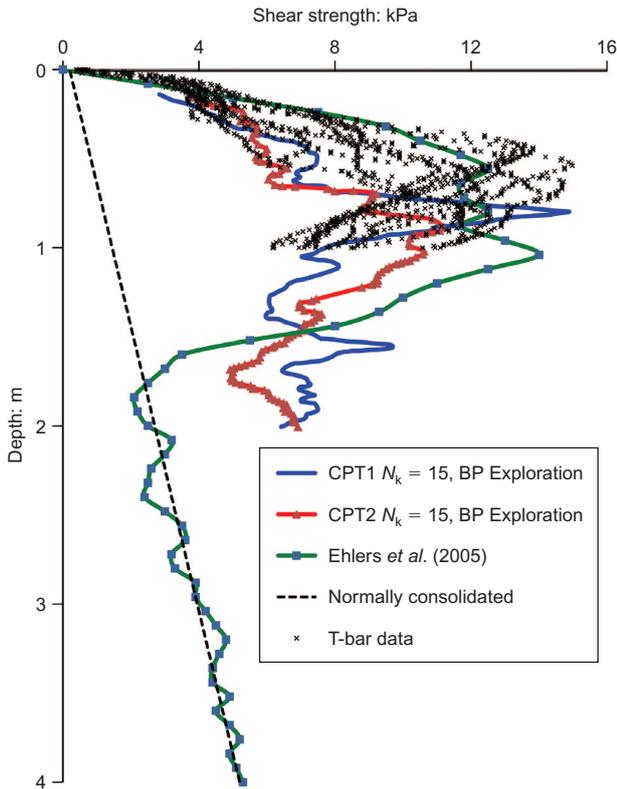


Fig. 1. Undrained shear strength profiles from cone penetration tests (CPTs) and T-bar tests, with normally consolidated strength trace assuming  $\gamma' = 2.5 \text{ kN/m}^3$

Numerous open burrows of various diameters and inclinations were distributed throughout the sediment, as identified during visual examination of split cores. X-ray computer tomography (CT) equipment (X-TEK) was used to image undisturbed core samples prior to laboratory testing, as shown in Fig. 2; the details of sample preparation and imaging are given in Kuo (2011). Burrows of diameter between 1 mm and 3 mm are observed, with random orientations in both the sub-vertical and sub-horizontal directions. Several authors have considered the influence of open burrows on sediment properties, especially in relation to

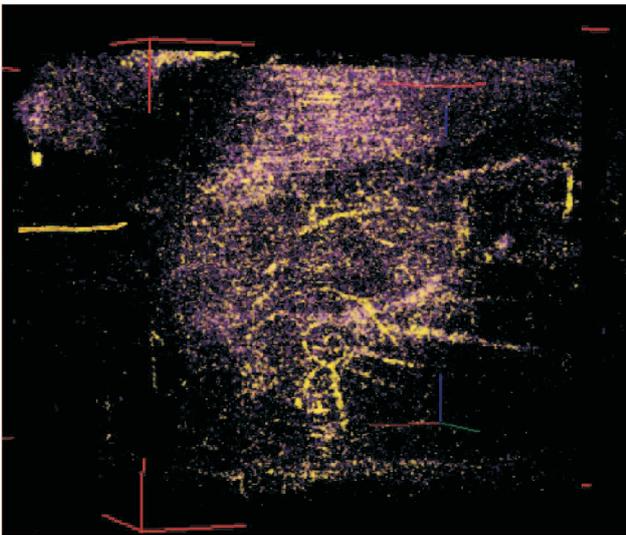


Fig. 2. Still image produced from X-ray computer tomography scanning of natural core samples. Light-coloured traces represent burrows of about 2 mm diameter

increased permeability and rate of consolidation (Meadows & Tait, 1989; Murray *et al.*, 2002).

#### Faecal pellets

Faecal pellets with a size comparable to that of rice grains were observed in box cores, as seen in Fig. 3. If they were found in samples analysed by previous investigators, however, they were apparently ignored. The particle size analysis of West African sediments was undertaken by Evans (2002) and Thomas *et al.* (2005), using a variety of techniques to disaggregate clay particles: see Fig. 4. Almost all of the heavily processed material passes the  $63 \mu\text{m}$  sieve, indicating that it is clay-sized or silt-sized.

Wet-sieving of a core through a  $225 \mu\text{m}$  sieve exposed thousands of smooth capsules, explaining the observation that the material appeared to contain sand-sized grains. Based on the available literature (e.g. Moore, 1931a; Martens, 1978; Bayliss & Syvitski, 1982), and expert advice (Gooday, personal communication, 2009), the capsules were identified as faecal pellets, which are produced by a variety of burrowing invertebrate species, including polychaetes. It was clearly necessary to investigate the possible influence on mechanical behaviour of such an abundance of faecal pellets within these sediments.

#### Faecal pellet percentages

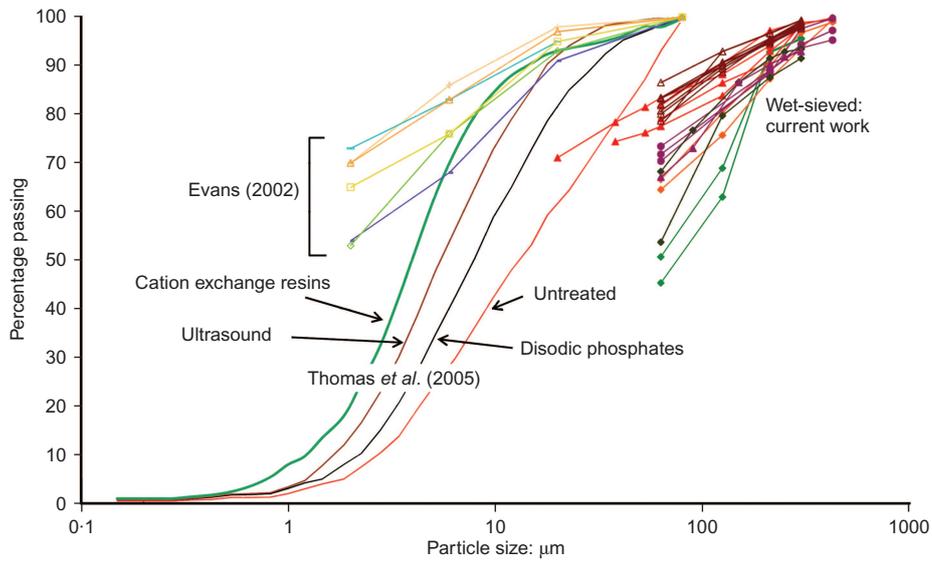
Conventional particle size distribution (PSD) analysis of clayey soils based on ASTM D442-63 (ASTM, 2007) was evidently an inappropriate method for investigating the pellets found within these sediments, owing to the mechanical breakage engendered during preparation. Pellet preservation was achieved through techniques used to prepare foraminifera samples by sedimentological washing. Bulk natural samples were carefully washed with running water through a series of sieves, without prior drying, crushing or remoulding. This ensured the survival of pre-existing biologically bonded aggregates. Results are presented as pellet percentages by original total dry mass, after measuring the water content of trimmings. The sieve sizes comprised  $425 \mu\text{m}$ ,  $300 \mu\text{m}$ ,  $212 \mu\text{m}$ ,  $125 \mu\text{m}$ ,  $75 \mu\text{m}$ ,  $63 \mu\text{m}$ ,  $53 \mu\text{m}$ ,  $38 \mu\text{m}$  and  $20 \mu\text{m}$ , with material passing the smallest sieve being discarded.

#### Faecal pellet wet-sieving results

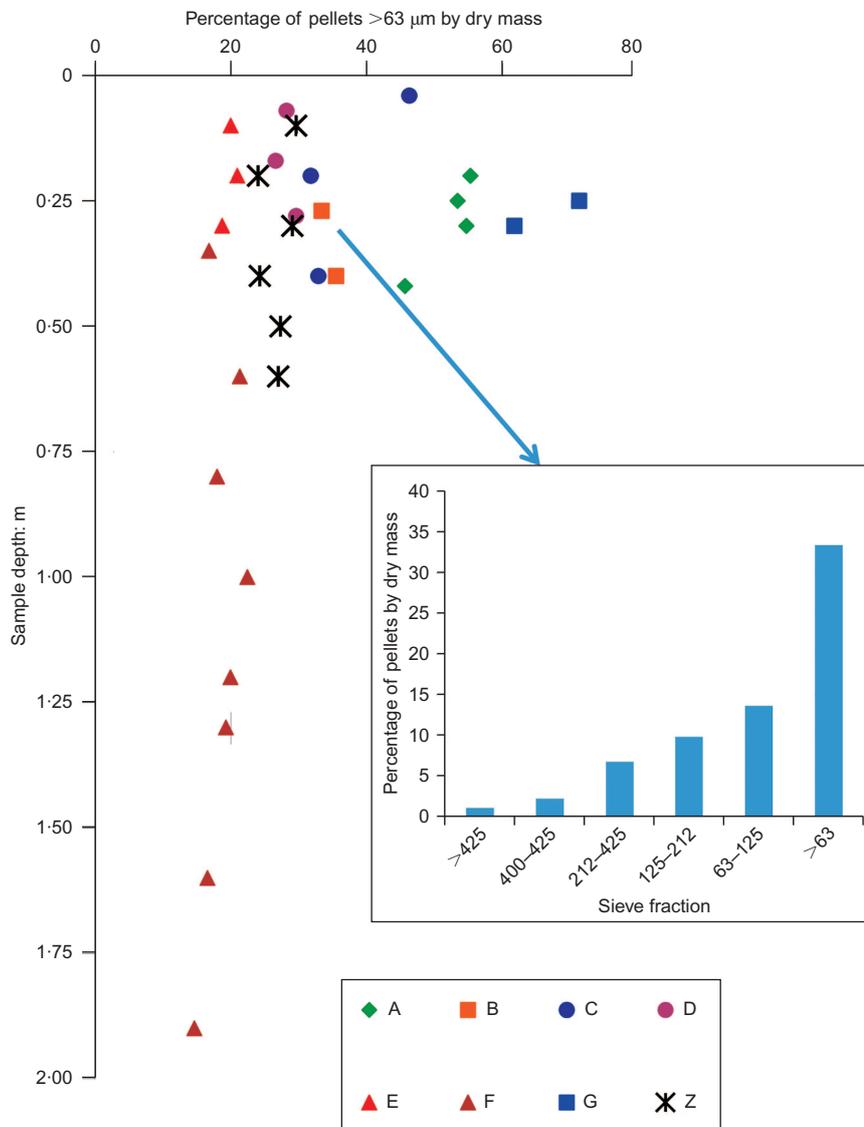
Cores from eight locations within the Gulf of Guinea, and from several depths, were wet-sieved to determine the percentages of faecal pellets larger than  $63 \mu\text{m}$ , shown in Fig. 5, with an indication of the percentage passing each sieve



Fig. 3. Core sample showing large, rice-grain-shaped faecal pellets of 3 mm diameter



**Fig. 4.** Particle size distribution curves from Evans (2002) and Thomas *et al.* (2005) compared with wet-sieved curves undertaken in this paper. Wet-sieving preserves pellets, and thus shifts the size distribution one order of magnitude coarser than conventional methods



**Fig. 5.** Results from wet-sieving of natural core samples, plotted as percentage of pellets greater than 63 µm by dry mass against sample depth. Insert: size distributions obtained from wet-sieving core B at 0.27 m depth

size for one particular sample (core B). Core B is typical in that the majority of pellets are in the 63  $\mu\text{m}$  to 125  $\mu\text{m}$  fraction, and the smallest percentage is found in the >300  $\mu\text{m}$  fraction. Cores A to G were associated with one project, and core Z represents samples from a different project. The results of core G are not considered representative of the crust material as a whole, because it contains a significantly high fraction of mineralised pellets. Results from this core will not be included in the following discussion concerning the crust.

Based on in situ and laboratory testing, the crustal strength observed in these samples generally develops from a depth of about 0.15 m below the sea-bed. Fig. 6 shows the relationship between the percentage of faecal pellets in the cores shown in Fig. 5 and the undrained shear strength obtained from adjacent penetrometer probes at the depth appropriate to the wet-sieved sample. This indicates that crusts contain about 20% to over 50% of faecal pellets by dry mass, and that there is an apparent correlation ( $R^2 = 0.75$ , for 17 samples from seven different locations) between the measured undrained strength and the proportion of faecal pellets. Note, however, that the sparsity of data leaves room for other hypothetical relationships, such as a constant, moderate strength with increasing pellet proportion up to about 50%, followed by a step rise in strength: see J in Fig. 6.

PSD profiles are included in Fig. 4 for comparison with previous testing undertaken by Evans (2002) and Thomas *et al.* (2005), illustrating the differences in PSD when samples are subject to different methods of preparation. If desiccated, remoulded and dispersed, as required by ASTM D442-63 (ASTM, 2007) and other similar methods, pellets will disintegrate into their constituent parts of clays, diatoms and detrital fragments, such as foraminifera and shell fragments, and sponge spicules. Careful wet-sieving of natural samples is shown to reveal particle sizes at least one order of magnitude larger than would otherwise be inferred.

#### MICROSCOPE OBSERVATIONS

Imaging of natural sediment containing pellets, and of wet-sieved pellets alone, was undertaken to illustrate the natural structure of samples, and to highlight the variability encountered in cores.

#### X-ray CT imaging and ESEM of faecal pellets

X-ray CT imaging was undertaken on core samples to identify worm burrows as seen in Fig. 2, following Kuo (2011). Environmental scanning electron microscopy (ESEM) was used to investigate the structure of intact pellets, as well as fragments of faecal pellets.

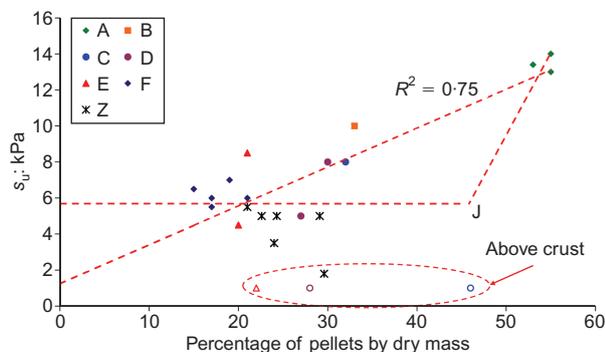


Fig. 6. Undrained shear strength determined from in situ T-bar profiles plotted against percentage of pellets by dry mass taken from natural core samples. Two proposed lines of best fit are presented

An ESEM image of a typical intact pellet is shown in Fig. 7, demonstrating the well-defined ellipsoidal, capsular shape. To determine whether the material smaller than 63  $\mu\text{m}$  also comprises faecal material, samples from 0.03 m, 0.2 m and 0.3 m depths were sieved to 20  $\mu\text{m}$ . Fig. 8 shows an ESEM image taken of material between 20  $\mu\text{m}$  and 53  $\mu\text{m}$ . This image shows that this fraction comprises silt-sized agglomerates of clay that have not dispersed during sieving. They do not exhibit the well-defined shape of the faecal pellet shown in Fig. 7; however, given their apparent compactness, they may represent pellets in various stages of decomposition. The material sieved to 20  $\mu\text{m}$  was found to contribute between 8% and 12% by dry mass to the percentage of non-clay-sized material, showing that Figs 5 and 6 underestimate the percentage of agglomerated material within natural crust samples.

The faecal pellet percentage above the crust is not significantly less than that within the crust: see Fig. 6. Based on previous studies, invertebrate activity is most prevalent within the upper tens of centimetres of sediment (Aller, 1982; Rhoads & Boyer, 1982; Meadows & Meadows, 1994; Murray *et al.*, 2002). This would suggest that most faecal material will be produced and deposited in this depth range. As discussed by Kuo *et al.* (2011), the sediment to a depth of about 0.15 m exhibits extremely high water contents

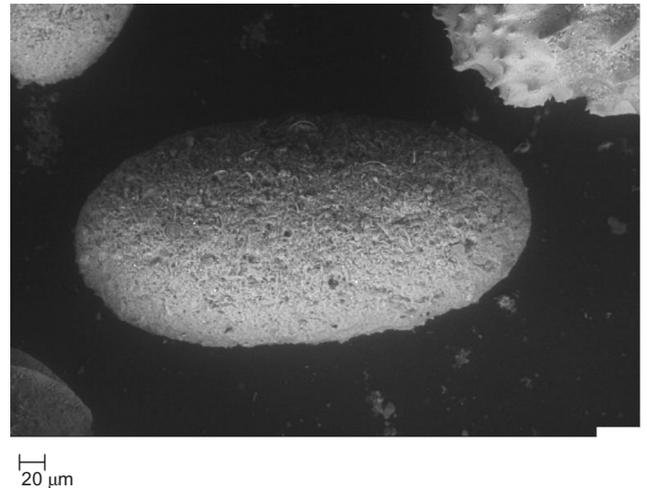


Fig. 7. Environmental scanning electron microscopy image of faecal pellet after wet-sieving

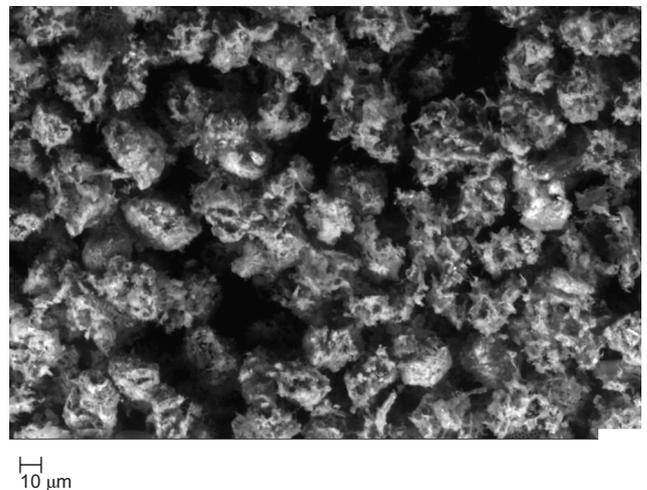


Fig. 8. Environmental scanning electron microscopy image of wet-sieved material from 20  $\mu\text{m}$  to 53  $\mu\text{m}$  showing agglomerates that are likely to be disintegrating faecal pellets

(often above 300%), and represents unconsolidated red ooze. It is therefore feasible that the crustal strength develops only when the sediment is subject to an effective confining stress due to overburden. Pellets are then no longer free to rearrange during shearing, but are restrained by an effectively stressed soil matrix. They are not free to dilate, because the voids between them are full of clay with a low permeability. The pellets therefore jam, and may crush.

Although core F in Fig. 5 shows a reduced proportion of pellets in the region below the crust, the precise reason for the loss of crustal strength remains to be clarified. An investigation of the possible mechanical destruction of pellets due to self-weight consolidation is described in Kuo & Bolton (2011).

Figure 9 presents ESEM images of washed pellets, which indicate the presence of microvoids within the structure of the pellets. These microvoids are observed to be less than 1–3  $\mu\text{m}$  in diameter. ESEM imaging with the variable pressure secondary electron (VPSE) detector also allows the identification of ‘wet textures’. Evidence for mucin or peritrophic membranes surrounding pellets (as discussed by Bayliss & Syvitski, 1982) is acquired using this method. The pellet membrane is produced within the gut of burrowing invertebrates to ease passage through the digestive system. Peritrophic membranes surrounding the pellet aid robustness by providing a protective sheath for the pellet contents. Mucus within the pellet, produced during digestion,

also enhances the strength by sticking the digested fragments together. By imaging with a backscatter detector in the same wet chamber as for VPSE imaging, information about the internal structure of pellets can be resolved. The arrangement of clay platelets at the pellet surface and microvoids within pellets is observed.

#### STRENGTH OF FAECAL PELLETS

##### *Prior evidence*

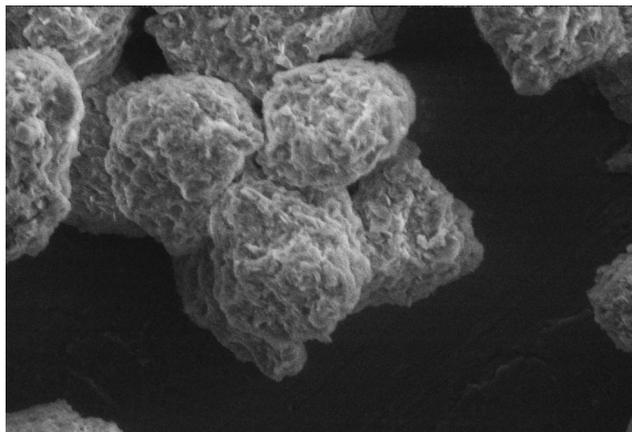
The faecal pellets observed in tested samples are likely to have been produced by a variety of invertebrate species. Their presence illustrates the significant biological influence of burrowing invertebrates on the crust material. The processes involved in pellet formation vary depending on species, but include activity within three sections of the digestion system: fore-gut, mid-gut and hind-gut (Barnes *et al.*, 1988). Factors that may influence the robustness of pellets, and their mechanical behaviour once excreted, include

- the presence in the fore-gut of salivary glands, which coat ingested food with mucus
- mechanical remoulding by contraction of muscle cells in the mid-gut wall (Barnes, 1974)
- desiccation by osmosis
- formation in the hind-gut of distinct pellets coated with mucus, described as ‘moulding’ by Barnes (1974) and ‘consolidating’ by Moore (1931a).

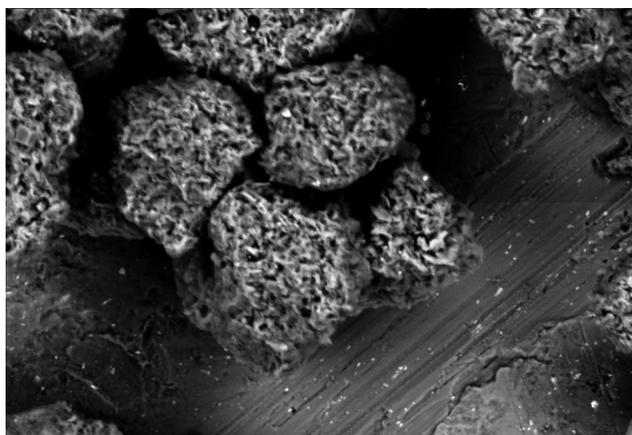
Moore (1931a, 1931b) discusses the faecal pellets in muddy sediments within the Clyde Sea area, west Scotland, which can represent the entire sediment. Pellet formation generally occurs close to the sediment/water interface, where animals have access to sufficient oxygen. By contrast, at greater sediment depths, conditions remain favourable for smaller and more robust creatures such as nematodes. Information relating to relative soil stiffness was reported by Moore (1931b), who observed comparatively stiff, clayey conditions at a depth of 0.2 m in the Clyde Sea sediments, which were separately reported to contain over 50% pellets ranging from 0.1 mm to 1 mm in length. This supports the proposition of a strong relationship between faecal pellets and sediment strength. The resilience of moulded pellets has also been noted by Moore (1931a), pellets being resistant to fairly rough handling, and able to withstand boiling in sulphuric acid and strong caustic soda. These observations led Moore (1931b) to suggest that pellets may remain in their pelletised form for hundreds of years in accumulating sediment. Thorp (1931) suggests, however, that the presence of bacteria in sediments surrounding pellets would tend to disseminate the internal contents, as the pellets become the food source for the next smaller order of organism.

##### *Faecal pellet crusher*

The strength of individual faecal pellets has not been explicitly investigated by previous researchers. To provide a quantifiable measure of pellet strength, a novel pellet-crushing device was designed, shown in Fig. 10. Individual pellets were placed on a saturated porous-plastic platform and covered with a thin, impermeable, plastic membrane. A suction,  $s$ , was applied to the pellets through the porous plastic in 0.1 kPa increments by lowering a reservoir of water (open to the atmosphere) relative to the porous-plastic platform. The plastic membrane was forced onto the pellets by the atmospheric pressure acting on the outside of the membrane. As most pellets encountered in the natural samples were between 63  $\mu\text{m}$  and 300  $\mu\text{m}$ , a microscope was



(a)



(b)

Fig. 9. Comparison of images produced when using (a) variable pressure secondary electron and (b) backscatter detectors in environmental scanning electron microscopy



Fig. 10. Faecal pellet crusher developed to measure undrained shear strength of faecal pellets

used to observe the point at which individual pellets crushed.

A typical example of a pellet before and after crushing is shown in Fig. 11. Pellets crushed at pressures ranging from about 0.1 kPa to 1 kPa. This represents a significant variation in pellet strength, which may be due to the age, stage of degradation, internal composition and in situ alteration experienced by the pellet post-excretion. The mechanism involved in the crushing of pellets using this pellet crusher is considered to approximate the crushing of grains between platens, with the pellet failing in tension at its mid-plane.

The conversion of suction  $s$  to an equivalent platen force is approximate, owing to the variable geometry of the flexible membrane. It is evident from the loading process that the pellet will experience an equivalent platen force equal to the relative suction inside the membrane multiplied by the area of membrane that drapes over the pellet. To determine accurately the nominal pellet stress at which crushing occurs, the elasticity and variance in shape of the plastic membrane need to be accounted for. As an initial estimation, it is assumed that the draped area for a typical pellet of diameter  $d$  and length  $2d$  can be approximated as

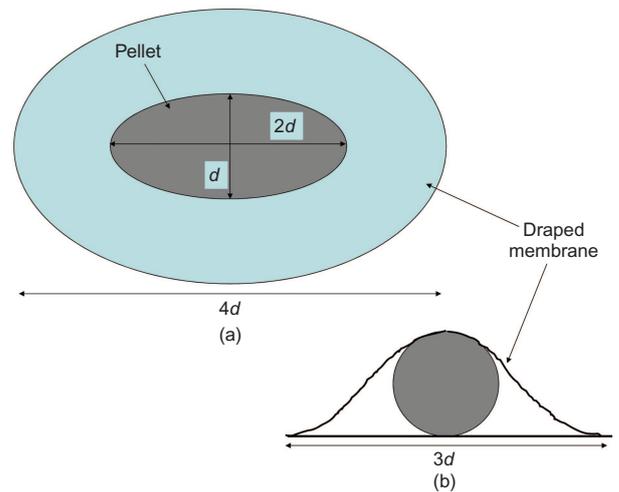


Fig. 12. Schematic diagram showing estimated drape area of plastic membrane over crushing faecal pellets

an ellipse with width  $3d$  and length  $4d$  (as shown in Fig. 12), which has an area  $3\pi d^2$ .

The faecal pellets split in tension on vertical failure planes, as shown in Fig. 11, which is similar to the fracture of glass spheres investigated by Shipway & Hutchings (1993). Based on their observation that the tensile stress  $\sigma_t$  at fracture for spheres of diameter  $d_{\text{sphere}}$  may be approximated by

$$\sigma_t = \frac{1.6F_c}{\pi d_{\text{sphere}}^2} \quad (1)$$

and taking an equivalent pellet diameter  $d_{\text{sphere}} \approx \sqrt{(2d \cdot d)}$ , with  $F_c \approx 3\pi d^2 s$ , we obtain

$$\sigma_t \approx 2.4s \quad (2)$$

Regarding the possible mass strength of faecal material in other modes of deformation, the unconfined compressive strength (UCS) can be estimated as ten times the tensile strength (e.g. Hudson & Harrison, 1997). The shear strength can then be estimated, conventionally, as one half of the UCS. The shear strength of individual pellets may therefore

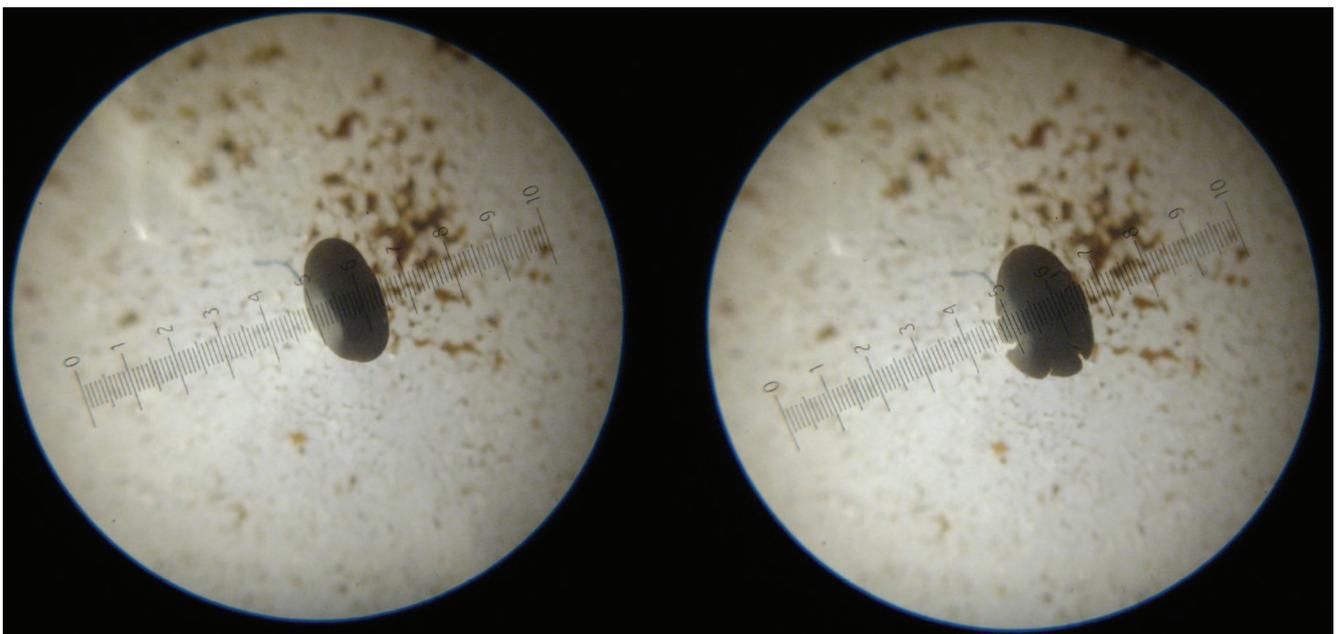


Fig. 11. Optical microscope image of a faecal pellet before (left) and after (right) crushing

range approximately from 1 kPa to 12 kPa. This is sufficient to establish that faecal pellets are strong enough to contribute significantly to crustal strength if they are sufficiently numerous.

## DISCUSSION

### *Significance of the abundance of pellets and agglomerates*

This paper demonstrates that although the crust material is of clay mineralogy, it consists predominantly of robust faecal pellets within a finer matrix, at least some of which is in the form of silt-sized clay agglomerates. The relatively good mechanical performance of this mixture must be explained. Studies of sand–clay mixtures by Vallejo & Zhou (1994) and of gravel–clay mixtures by Kumar & Muir Wood (1999) demonstrated that the volumetric percentage of granular material required to influence the mechanical properties of the mixture significantly is approximately 50%. Below this granular percentage, the strength remained largely that of the clay. Their explanation is that a volumetric proportion of 50% sand is required to create a granular void ratio in the vicinity of unity, treating the clay as a void filler. A void ratio of unity is typical of  $e_{\max}$  values at which a loose assemblage of similar grains (here to be taken as pellets) just comes into mutual contact.

A micromechanical model will be helpful in understanding this phenomenon in relation to the current discussion of the behaviour of crust material containing faecal pellets. For a volumetric concentration of grains in excess of about 50%, the shearing of the composite material will cause jamming of grains, and induce a tendency to dilate. Because the grains are surrounded by a saturated low-permeability matrix, this tendency to dilate will be suppressed, and replaced by the tendency to generate negative excess pore pressures in the fine matrix as the mixture shears at constant volume. This, in turn, will lead to enhanced intergranular stresses within both the granular skeleton and the clay matrix, and this will be perceived as enhanced shear strength. What has been described here is simply the initiation of shear flow in a jammed assemblage of particles, in which the initial mean effective stress increases markedly to the critical-state stress at which shear can take place without volume change.

If the granular skeleton consists of faecal pellets, the enhanced effective stresses due to jamming can equally lead to their breakage. The >50% proportion of faecal pellets in core A, as shown in Fig. 5, and the significant shear strength deduced from the pellet-crushing experiments, appear to explain the significant crustal shear strength in that core. However, a consideration of the strengths of other cores in relation to their proportion of pellets challenges this elementary association.

If the pellets in the current study had the same water content as the matrix material surrounding them, it would follow that a 50% pellet fraction by dry mass would correspond with a 50% fraction by volume. However, faecal pellets were found to have an average water content of 150% in the tested crust samples, while the silt–clay matrix had a water content of about 200%. This means that 54% by mass of pellets corresponds to 50% by volume, and a pellet void ratio of 1. Only the most pellet-rich cores reach this target in Fig. 5, and yet Fig. 6 demonstrates an apparent correlation between the measured strength of crust material and the proportion of pellets found in samples. Furthermore, even where the proportion of pellets was found to be quite low, such as in core F with 20% by dry mass or about 17% by volume, the shear strength of the mixture was found to be about 6 kPa. This is an order of magnitude higher than the expected undrained strength of a normally consolidated sediment of high-plasticity clay, calculated approximately as

$0.5\sigma'_v$ , following Skempton (1954). With an effective unit weight of  $2.5 \text{ kN/m}^3$  at a depth of 0.25 m corresponding to the core samples with about 20% pellets, the calculated strength would be only about 0.25 kPa for a normally consolidated sediment. The finding of Kumar & Muir Wood (1999) is that 22% of granular inclusions by volume is insufficient to enhance the strength of a matrix of fines. The most plausible explanation is therefore that the silt–clay matrix between the pellets is, itself, providing the mass strength of about 6 kPa observed in Fig. 6.

Previous authors have noted the existence of agglomerates (flocs), including Pamukcu & Tuncan (1991), for example. Reynolds & Gorsline (1992) mention ‘physico-chemical flocs which are roughly equidimensional, but boundaries between them are generally poorly defined’, and ‘bioflocs which are thought to result from biological agglomeration during ingestion by benthic and pelagic organisms. These are more densely packed flocs containing mostly face/face (FF) or low-angle edge/face (EF) clay particle contacts; organism tests are a common constituent. Bioflocs are equidimensional, usually ovoid; the individual flocs are well-defined.’ Although there is obvious confusion in this account between faecal pellets and their constituent agglomerates, the notion of biologically formed, densely packed agglomerates may hypothetically be associated with the silt-sized agglomerates of clay that constitute 95% of the Gulf of Guinea material when PSDs are undertaken on untreated soil (Fig. 4), of which the >20  $\mu\text{m}$  fraction was pictured in Fig. 8. It seems very likely that these agglomerates are the broken-down remains of faecal pellets, and that they retain some of the strong internal bonding of their antecedents. This melange of robust, silt-sized agglomerates forms the effective skeleton of the soil matrix that surrounds the faecal pellets within the crustal zone. It is this material that presumably provides the 6 kPa undrained shear strength seen in crustal cores with 25% faecal pellets, and which must be the origin of the ‘structure’ referred to by De Gennaro *et al.* (2005) as the presumed cause of the apparent yield stress being greater than the current vertical effective stress, by an amount that is reported by Colliat *et al.* (2011) as being typically 5–30 kPa at depths up to 20 m. Where, in addition, there are greater than 50% faecal pellets, the strength is even greater. Referring back to Fig. 6, the preferred relationship between undrained strength and pellet proportion is that marked J.

### *Particle size distribution*

This research has highlighted the importance of the natural structure of sediment. The presence of faecal pellets that are either deposited in situ by burrowing invertebrates, or transported some distance prior to sedimentation, can affect sediment behaviour. The current practice of undertaking a PSD on core samples following standards such as ASTM D442-63 (ASTM, 2007) will result in a significantly skewed interpretation of the grain size. This is due to the remoulding and destruction of all natural fabric prior to the analysis, resulting in a PSD interpretation of the soil as clay. If faecal pellets and clay agglomerates were structurally weak, and represented only temporary structures within the crust, they might be expected to crush under pipe stresses. However, faecal pellets have been shown to exhibit significant robustness, and the same has been inferred for the finer, more irregular agglomerates. From their observed strengths, these components of the soil may survive under the small effective stresses delivered by pipelines, so their presence in the PSD needs to be recognised.

It is therefore concluded that the wet-sieving of marine sediments, preferably to 20  $\mu\text{m}$ , should be routinely undertaken to provide an accurate indication of the natural

sediment's grain size distribution. The results of this analysis will aid in the interpretation of interface shear tests and the consolidation behaviour of natural samples. These results are the key to understanding the behaviour of hot pipelines installed into these sediments.

#### Biology: the origin of the crust

The literature indicates that biological processes occur predominantly within the benthic boundary layer, in close proximity to the sea-bed/water interface. No actual invertebrates were found in the core samples of deep ocean crustal sediment recovered from West Africa. Their presence in situ is irrefutable, however, based on the abundant physical evidence for bioturbation in the form of open burrows and faecal pellets. The experimental work described above has demonstrated the abundance of individual pellets through wet-sieving and their robustness through crushing tests. The correlation of crustal strength with abundant bioturbation, in the form of faecal pellets and burrows, strongly suggests that biology in some form is the cause both of the crust and of its ultimate degeneration.

A study by Gingras *et al.* (2008) estimates rates of bioturbation for a range of invertebrate species. It is suggested that ten worms may require less than 15 years to completely bioturbate a  $1\text{ m} \times 1\text{ m} \times 0.1\text{ m}$  volume of sediment, which is equivalent to  $0.75\text{ mm/year}$  with worms at  $1\text{ m}$  centres on plan. The estimated rate of sedimentation in the West African sediments is only  $0.1\text{ mm/year}$ . It is therefore feasible for worms, through their daily activities, to engineer into pellets all the material that falls to the sea-bed.

The existence of a relatively thin crust at the sea-bed, and the correlation in Fig. 6 between the proportion of faecal

pellets and the shear strength of the local crustal material, even when the pellets are not sufficiently numerous to have contributed directly to that strength, supports the contention that pellets are continually being broken down into robust agglomerates such as those in Fig. 8. These agglomerates must themselves be vulnerable to attack, since they may be reduced to a clay fabric that is normally consolidated under the effective overburden. Such a deterioration is not inevitable, however: Colliat *et al.* (2011) show a variety of strength distributions below  $1\text{ m}$  depth in these sediments. A shallow sediment that is rich in faecal pellets will probably also be rich in agglomerates, and can have a substantial crustal strength. A sediment that is less rich in pellets may still have a significant component of agglomerates, and still display a strength much higher than that expected of a normally consolidated sediment. But at somewhat greater depth, where it is observed that there are few faecal pellets, the processes of degradation must be assumed to have overwhelmed both pellets and their derived agglomerates, so that the strength of the sediment falls to its normally consolidated value.

The proposed biological genesis of crust sediments, and their ultimate degeneration, is depicted in Fig. 13 in parallel with strength profiles from in situ T-bar tests and CPTs. Robust faecal pellets are continuously being created and replenished by burrowing invertebrates working mainly within  $0.5\text{ m}$  of the seafloor, as they digest nutrients from the above ocean. The loss of strength at sediment depths greater than  $1\text{ m}$  coincides with a sparseness of pellets. By this depth, the sediment is approximately  $10\,000$  years old, which is a significant period of time for biological agents such as nematodes or bacteria, or for chemical processes such as cation exchange, to break down the crust material, releasing

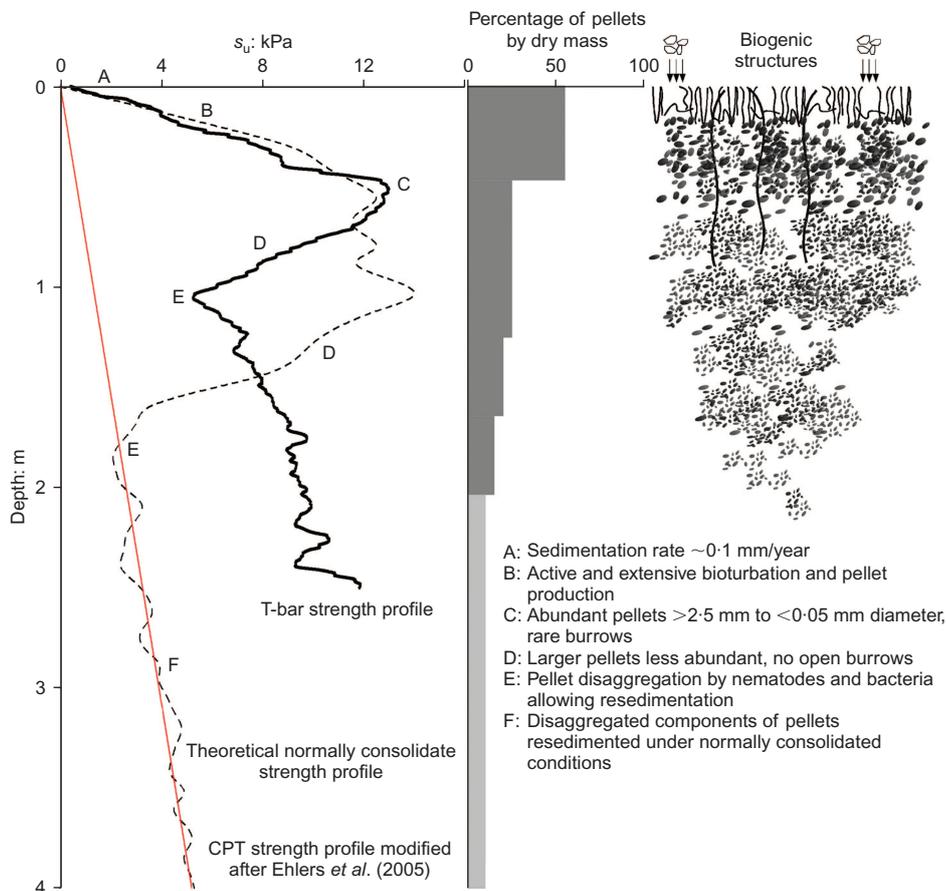


Fig. 13. Summary of proposed biological genesis of crust sediments, shown adjacent to in situ strength measurements

clay platelets to form a normally consolidated sediment below the crust.

## CONCLUSIONS

There is palpable evidence of the activities of invertebrates such as polychaete worms in the shallow sediments found in deep water in the Gulf of Guinea, in the form of open burrows and of great numbers of faecal pellets, ovoid in shape and typically sized between 60 and 300  $\mu\text{m}$ .

The crust found at shallow depths up to 1 or 2 m below the seafloor in the Gulf of Guinea has an undrained shear strength ranging up to about 15 kPa, one or two orders of magnitude larger than expected for a normally consolidated clay sediment. By wet-sieving 19 samples from natural cores at seven sites, it has been discovered that this crustal strength correlates ( $R^2 = 0.75$ ) with the proportion of faecal pellets found at each location. Samples with over 50% faecal pellets by volume display strengths over 12 kPa.

A novel pellet crusher has been developed, in which a pellet resting in a pool of water upon a porous pedestal is crushed by suction. Tensile strengths between 0.2 and 2 kPa are inferred, implying that pellet material has an unconfined compressive strength in the range 2–24 kPa.

These faecal pellets are, therefore, sufficiently robust to explain the  $\sim 12$  kPa shear strength at certain locations of the deep ocean crust, but only if they are sufficiently numerous to form an interconnected skeleton. However, even samples with only 25% pellets manage to register a shear strength of  $\sim 6$  kPa, which is still an order of magnitude greater than normally consolidated material of the same depth and density. This is attributed to irregular clay agglomerates, examples of which were retained on a 20  $\mu\text{m}$  sieve during wet-sieving. These may well be fragments of pellets degraded by other organisms, such as nematodes or bacteria.

The most likely explanation for the creation of the crust just below the red ooze is that invertebrates such as polychaete worms are sufficiently active over a depth of  $\sim 0.5$  m to consume and excrete that entire layer, forming faecal pellets. The sediment may be strongly agglomerated in the acid environment of the worms' guts, and the resulting pellets may also be desiccated by osmosis and compacted in the gut. Such pellets behave initially not as free clays but as bonded or overconsolidated clays.

However, other biological agents simultaneously begin to degrade pellets to capture mucins and other nutrients, and the first products of this disintegration are irregular but robust agglomerates. At 1 m depth in the crust, the rate of creation of new burrows and pellets will be negligible, so the agencies of degradation will be dominant. Furthermore, the timescale involved in laying 1 m of crust is about 10 000 years, so there is plenty of time for these as yet unidentified agents to free the clay platelets from their bonds and re-create a normally consolidated sediment, lying below about 2 m.

As oil and gas exploration continues to expand into deeper waters around the world, the phenomenon of deep-sea clay crusts will become more familiar to industry and academic research. With their origin now discovered, as described by this paper, the industry should have greater confidence in the mechanical characterisation and testing of these sediments.

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## NOTATION

$d$	pellet diameter
$d_{\text{sphere}}$	sphere diameter
$e_{\text{max}}$	maximum void ratio
$F_c$	crushing force on a pellet
$I_p$	plasticity index
$N_k$	cone factor
$R^2$	coefficient of correlation
$s$	suction
$s_u$	undrained shear strength
$\gamma'$	submerged effective unit weight
$\mu$	axial soil–pipeline coefficient of friction
$\sigma_t$	tensile stress
$\sigma'_v$	effective vertical stress

## REFERENCES

- Aller, R. C. (1982). The effects of macrobenthos on chemical properties of marine sediment and overlying water. In *Animal sediment relations: the biogenic alteration of sediments* (eds P. L. McCall and M. J. S. Tevesz), pp. 53–102. New York, NY, USA: Plenum Press.
- ASTM (2007). *ASTM D422-63: Standard test method for particle-size analysis of soils*. West Conshohocken, PA, USA: ASTM International.
- Barnes, R. D. (1974). *Invertebrate zoology*, 3rd edn. Philadelphia, PA, USA: W. B. Saunders.
- Barnes, R. S. K., Calow, P. & Olive, P. J. W. (1988). *The invertebrates: a new synthesis*, 1st edn. Oxford, UK: Blackwell Scientific.
- Bayliss, P. & Syvitski, J. P. M. (1982). Clay diagenesis in recent marine fecal pellets. *Geo-Mar. Lett.* **2**, No. 1–2, 83–88.
- Borel, D., Puech, A., Dendani, H. & de Ruijter, M. (2002). High quality sampling for deep water geotechnical engineering: the STACOR experience. *Proceedings of the conference on ultra-deep engineering and technology*, Brest.
- Bruton, D. A. S., Carr, M. & White, D. J. (2007). The influence of pipe-soil interaction on lateral buckling and walking of pipelines: the SAFEBUCK JIP. *Proc. 6th Int. Conf. on Offshore Site Investigation and Geotechnics, London*, 133–148.
- Colliat, J. L., Dendani, H., Puech, A. & Nauroy, J.-F. (2011). Gulf of Guinea deepwater sediments: geotechnical properties, design issues and installation experiences. *Proc. 2nd Int. Symp. on Frontiers in Offshore Geotechnics (ISFOG-II), Perth*, 59–86.
- De Gennaro, V., Delage, P. & Puech, A. (2005). On the compressibility of deepwater sediments of the Gulf of Guinea. *Proc. 1st Int. Symp. on Frontiers in Offshore Geotechnics (ISFOG 2005), Perth*, 1063–1069.
- Ehlers, C. J., Chen, J., Roberts, H. H. & Lee, Y. C. (2005). The origin of near-sea floor crust zones in deepwater. *Proc. 1st Int. Symp. on Frontiers in Offshore Geotechnics (ISFOG 2005), Perth*, 927–933.
- Evans, T. (2002). *Block 18 offshore Angola*, Technical Report 20021117-1. Oslo, Norway: Norwegian Geotechnical Institute.
- Gingras, M. K., Pemberton, S. G., Dashtgard, S. & Dafeo, L. (2008). How fast do marine invertebrates burrow? *Palaeogeog. Palaeoclimatol. Palaeoecol.* **270**, No. 3–4, 280–286.
- Hudson, J. A. & Harrison, J. P. (1997). *Engineering rock mechanics: An introduction to the principles*. Oxford, UK: Elsevier.
- Kumar, G. V. & Muir Wood, D. (1999). Fall cone and compression tests on clay-gravel mixtures. *Géotechnique* **49**, No. 6, 727–739, <http://dx.doi.org/10.1680/geot.1999.49.6.727>.
- Kuo, M. Y.-H. (2011). *Deep ocean clay crusts: behaviour and biological origin*. PhD thesis, University of Cambridge, UK.
- Kuo, M. Y.-H. & Bolton, M. D. (2011). Faecal pellets in deep marine soft clay crusts: implications for hot-oil pipeline design. *Proc. 30th Int. Conf. on Ocean, Offshore and Arctic Engineering, Rotterdam*, 883–892.
- Kuo, M. Y.-H., Hill, A., Rattley, M. & Bolton, M. D. (2011). New evidence for the origin and behaviour of deep ocean 'crusts'. *Proc. 2nd Int. Symp. on Frontiers in Offshore Geotechnics (ISFOG-II), Perth*, 365–370.
- Martens, P. (1978). Faecal pellets. *Fich. Ident. Zooplancton* **162**, 1–4.

- Meadows, A. & Meadows, P. S. (1994). Bioturbation in deep-sea Pacific sediments. *J. Geol. Soc.* **151**, No. 2, 361–375.
- Meadows, P. S. & Tait, J. (1989). Modification of sediment permeability and shear-strength by 2 burrowing invertebrates. *Mar. Biol.* **101**, No. 1, 75–82.
- Moore, H. B. (1931a). The specific identification of faecal pellets. *J. Mar. Biol. Assoc. (New Ser.)* **17**, No. 2, 359–365.
- Moore, H. B. (1931b). The muds of the Clyde Sea Area. III. Chemical and physical conditions; rate and nature of sedimentation; and fauna. *J. Mar. Biol. Assoc. (New Ser.)* **17**, No. 2, 325–358.
- Murray, J. M. H., Meadows, A. & Meadows, P. S. (2002). Biogeomorphological implications of microscale interactions between sediment geotechnics and marine benthos: a review. *Geomorphology* **47**, No. 1, 15–30.
- Pamukcu, S. & Tuncan, M. (1991). Influence of some physicochemical activities on mechanical behaviour of clays. In *Microstructure of fine-grained sediments: from mud to shale* (eds R. H. Bennett, W. R. Bryant and M. H. Hulbert), pp. 241–253. New York, NY, USA: Springer-Verlag.
- Reynolds, S. & Gorsline, D. S. (1992). Clay microfabric of deep-sea, detrital mud(stone)s, California continental borderland. *J. Sediment. Res.* **62**, No. 1, 41–53.
- Rhoads, D. C. & Boyer, L. F. (1982). The effects of marine benthos on physical properties of sediments: a successional perspective. In *Animal sediment relations* (eds P. S. McCall and M. J. S. Tevesz), pp. 3–52. New York, NY, USA: Plenum.
- Shipway, P. H. & Hutchings, I. M. (1993). Attrition of brittle spheres by fracture impact loading under compression and impact loading. *Powder Technol.* **76**, No. 1, 23–30.
- Skempton, A. (1954). Discussion of the structure of inorganic soil. *J. Soil Mech. Found. Div. ASCE* **80**, 19–22.
- Stewart, D.P. & Randolph, M.F. (1994). T-bar penetration testing in soft clay. *J. Geotech. Engng ASCE* **120**, No. 12, 2230–2235.
- Thomas, F., Rebours, B., Nauroy, J.-F. & Meunier, J. (2005). Mineralogical characteristics of the Gulf of Guinea deep water sediments. *Proc. 1st Int. Symp. on Frontiers in Offshore Geotechnics (ISFOG 2005), Perth*, 1055–1061.
- Thorp, E. M. (1931). Description of the deep-sea bottom samples from the western North Atlantic and the Caribbean Sea. *Bull. Scripps Inst. Oceanogr., Tech. Ser.* **3**, No. 1, 1–31.
- Vallejo, L. E. & Zhou, Y. (1994). The mechanical properties of simulated soil-rock mixtures. *Proc. 13th Int. Conf. Soil Mech. Found. Engng, New Delhi* **1**, 365–368.
- White, D. J. & Cheuk, J. C. Y. (2008). Modelling the soil resistance on seabed pipelines during large cycles of lateral movement. *Mar. Struct.* **21**, No. 1, 59–79.