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Experiments on the entrainment threshold of well-sorted and poorly sorted carbonate sands

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ABSTRACT

Few studies have examined the hydrodynamic behaviour of carbonate sediments. The data presented here are the result of preliminary research on entrainment in well- and poorly sorted carbonate sands. Experiments were performed using naturally occurring sediments in a tilting, recirculating freshwater flume. Results indicate that when of similar size, shape and density, the transport threshold of carbonate sands is similar to that of quartz. However, owing to their lower density and often platy or irregular shape, skeletal sands require a lower shear stress to initiate transport. Because the density of carbonate particles may increasingly vary with grain size, the threshold of motion in coarse carbonate grains may differ more markedly from that of quartz. In poorly sorted samples, results show that the coarse-grained constituents move before the finer-grained components. Grain properties and boundary-layer dynamics are believed to explain this phenomenon. Rollability of the larger grains combined with physical trapping and immersion within a low velocity sublayer are believed to prevent finer particles from moving. Given the appropriate sediments and flow conditions, it may therefore be possible to deposit and preserve fine-grained sediments in a flow regime typically thought to transport such materials.

INTRODUCTION

Numerous studies have focused on the critical shear stress or velocity of fluid flow that cause the inception of grain motion. A comprehensive review of these data was presented by Miller *et al.* (1977) and Yalin & Karahan (1979). Only a limited number of these investigations have examined the entrainment of non-quartz sands (Southard *et al.*, 1971; Mantz, 1977; Miller & Komar, 1977; Young & Southard, 1978; Young & Mann, 1985), poorly sorted sediments, or those with varying densities (Wiberg & Smith, 1987; Wilcock, 1988, 1993; Wilcock & Southard, 1988; Li & Komar, 1992). Because natural sands are variable in composition and sorting, and the hydrodynamic behaviour of sediment partly controls fundamental geological processes, further study of other relatively common and distinct sedimentary materials is needed. The data presented here represent preliminary research into the transport threshold of both well-sorted and poorly sorted carbonate sands.

Carbonate sediments form both organically and inorganically; consequently they can vary widely in density and shape. These properties, along with fluid flow and bedform morphology, control the beginning of grain movement. Given that carbonates and mixed carbonate–siliciclastic sediments are common in modern and ancient marine environments, understanding their hydrodynamic behaviour is important for predicting and interpreting depositional processes.

PREVIOUS RESEARCH

Three parameters are needed to understand and predict sediment transport: (1) the geological

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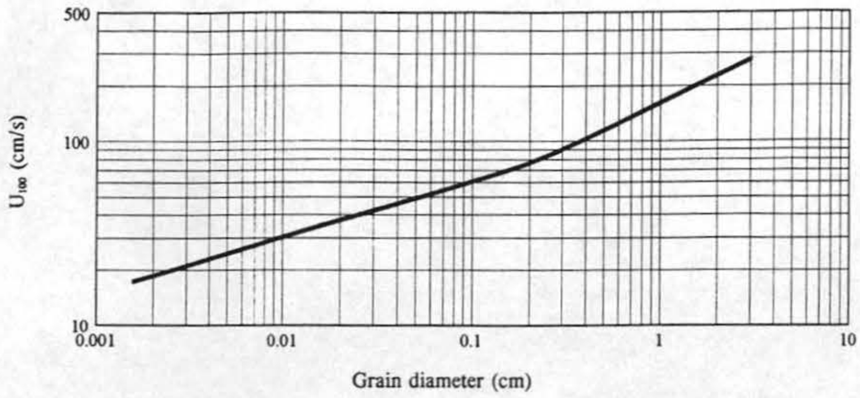

Fig. 1. Critical shear stress as a function of grain diameter for quartz sediments in 20°C water (after Miller *et al.*, 1977).

properties of the sediments and bed surface, (2) the nature of fluid flow over that surface and (3) the relationship between (1) and (2), which results in particle entrainment. Empirical relationships between grain parameters and undirectional fluid flow have been used to define the threshold at which sediments become entrained. Early work into the entrainment problem was conducted by Hjulstrøm (1935), who related the mean velocity of river flow to the grain size of quartz bed particles. Shields (1936) produced a dimensionless entrainment function θ_t based on the density ρ_s of quartz grains, grain diameter D, fluid density ρ, kinematic fluid viscosity υ, and the bed shear stress τ_0 of the fluid flow, as well as the acceleration of gravity g:

$$\theta_t = \tau / (\rho_s - \rho) g D. \quad (1)$$

A plot of θ_t against the dimensionless boundary Reynolds number ($Re^* = u^* D / \upsilon$, where u^* is the shear velocity) is known as the Shields curve. This relationship remains the basis for much of today's applied and theoretical research. However, because τ_0 and D are input variables on each axis, an iterative process is required to determine the threshold shear stress for a particular grain diameter, or to find the largest particle diameter transported by a given shear stress. Several means of combating this problem have been suggested. Vanoni (1964) incorporated a curve based on fluid and grain properties into the Shields diagram which when combined with the Shields curve allowed for the calculation of the critical shear stress for a given sediment. In another method, Yalin (1972) eliminated u^* and thus τ_0 in the abscissa by combining θ_t and Re^*. The Yalin parameter $Re^{*2} / \rho \upsilon^{-2}$ plotted against θ_t has the same general form as the Shields curve, but allows for direct determination of the threshold θ_t from the fluid and grain characteristics. Another approach has been to redefine the axis so that each contains either D or τ_0, but not both. An example of this is shown in Fig. 1, after Miller *et al.* (1977), specifically for quartz-density sediments in 20°C water. Various researchers have developed other threshold formulae (Komar & Miller, 1974; Swart, 1974; Hallermeier, 1980) or proposed the use of settling velocity rather than grain diameter as the significant sediment parameter (Komar & Clemens, 1986). However, the Shields curve or a modified version remains the most widely accepted and applied entrainment relationship.

Several authors have pointed out that one of the difficulties in using entrainment data is the variety of definitions used for the threshold of motion (Miller *et al.*, 1977; Wilcock, 1988). Two main problems are faced in defining initial motion: (1) the shear stress determined to define initial motion can be recognized only after it actually exceeds critical, and grain motion occurs, and (2) because bed shear stress is a fluctuating phenomenon, it is not possible to define a value below that which produces motion. A definition of initial motion based on critical shear stress is needed to compare both theoretical and empirical studies. Experimental and field studies have based initial motion primarily on either observations of grain movements per unit area or a minimal transport rate. In this study, a minimal transport rate is measured and the threshold of sediment transport is defined by a velocity of flow which produces movement, but not significant transport. Because bedform development or the production of scour structures provide clear evidence of significant transport, all flume runs in which these occurred were considered to be above the threshold condition.

Carbonate grains vary in shape and density due to the diversity of organic and inorganic processes by which they form. Furthermore, they are subject to alteration by processes such as pore filling, micritization and encrustation. Whereas density and shape, along with fluid flow, largely control the hydrodynamic behaviour of granular materials, the exact relationship between entrainment and a velocity threshold or critical shear stress in carbonate sediments and mixed carbonates–siliciclastics may differ from that of quartz grains. One *in situ* study (Young & Mann, 1985) suggests that entrainment values for carbonate grains fall below the accepted curves for spherical grains, and when corrections for grain shape are made, only a slight improvement in the fit to the curves is found. Other research on the effect of grain shape in siliciclastics suggests that cohesionless flakes require a lower incipient transport stress than do cohesionless spherical grains (Mantz, 1977). Because carbonate grain shapes and density vary, the hydrodynamic behaviour differs depending on composition (e.g. coralline algae, mollusc shell or *Halimeda*).

EXPERIMENTAL PROCEDURES

Sediments

Naturally occurring carbonate sands were collected from various marine environments using snorkelling gear. Two sediment samples were collected from the Bahamas: (1) a well-sorted, relatively homogeneous, 0·5-mm ooid sand from the shallow shoals at Joulter's Cay, and (2) a more heterogeneous sample from a patch reef near Lee Stocking Island. Sediments were also collected from Horseshoe Reef within the Tobago Cays, Grenadines. These sands were split into two subsamples: (1) an unsieved, poorly sorted mix of skeletal materials, and (2) a sieved sample of grains 0·5 mm in size. In addition, a naturally well-sorted, 0·5-mm sand, containing both carbonate and terrigenous materials, was collected from Green Cay in the British Virgin Islands. All of these sediments were washed in dilute bleach (sodium hypochlorite) prior to flume experiments. This procedure, as outlined in Pingitore *et al.* (1993), removed all live algae and/or bacteria from the sediments to prevent biological binding of grains during transport experiments. Grain size of sediment samples was analysed using standard sieve techniques, and composition was determined through grain counts under a binocular microscope. Both naturally homogeneous sands and those sieved were observed to be well-sorted in shape as well as size. Furthermore, due to their composition and relatively small size, density variations among the grains of these samples are expected to be small. Consequently, although standard sieve techniques will not always produce a sample sorted in terms of hydraulic properties, in this case due to the relatively small size of the grains, their similar shape and composition, sieving is believed to have sorted the samples in terms of size and hydraulic behaviour. A well-rounded, 0·5-mm, clean quartz sand was obtained from the US Silica Company for comparative purposes in flume experiments.

Flume preparation and flow properties

A tilting, recirculating freshwater flume, 9 m long by 0·16 m wide, was used for transport experiments. The downstream end of the flume contained a bed of sediments 3 m long and $\sim$1 cm thick. A sediment trap was constructed at the downstream end of the flume to collect all of the materials transported along the bed during experiments. The upstream section of the flume contained a false bottom at the same elevation as the sediment layer. Sediment, with a grain diameter of 0·5 mm, was glued to the downstream 2 m of the false bottom to establish a boundary layer approximately like that over the test bed. To ensure uniform flow, depth was kept relatively constant along the flume by adjusting the slope.

Before each run, the sediment bed was smoothed to ensure that no bedforms were present. Flow velocity was slowly increased while the flume slope was carefully adjusted to keep depth uniform. Timing for each experiment began once grains could be seen to move and transport was taking place. Each run lasted 15 min, during which surface velocity over the sediment bed was measured. During several of the flume runs, measurements of surface velocity were made at several positions along the flume as well as throughout the 15-min interval to ensure uniform flow over space and time. Sediments were collected after each run from the downstream trap, dried and weighed.

Surface velocities in the flume were measured using small floats. Calculations were performed based on the following assumptions to derive shear velocity at the bed from surface flow. In an open channel, flow may be considered rough or smooth depending on the scale of the bed roughness k, relative to thickness of the viscous sublayer. Daily & Harleman (1966) suggest an admissible roughness, k_{adm}, which when less than or equal to 100 υ/U, determines if the flow can be considered smooth. Using the measured

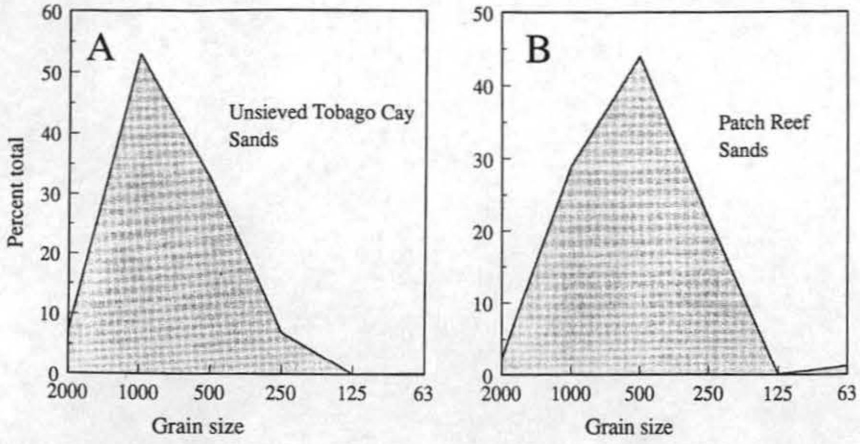

Fig. 2. Grain-size distribution (μm) of poorly sorted Tobago Cay (A, unsieved) and Patch Reef (B) sands.

Table 1. Results of flume runs, calculations and sediment property measurements.

Sample	D_{50} (mm)	ρ_s (g cm^{-3})	u_s (cm s^{-1})	u^* (cm s^{-1})	τ_0 (dynes cm^{-2})	θ_t	Re^*	Yalin	U_{100}	Runs
Quartz	0·5	2·66	27·32	1·47	2·17	0·027	7·35	45	38·04	12
Ooids	0·5	2·77	25·50	1·37	1·89	0·022	6·86	47	33·18	9
Tobago(s)	0·5	2·50	23·86	1·28	1·66	0·023	6·42	43	31·05	12
Green Cay	0·5	2·73	27·90	1·50	2·72	0·027	7·51	46	36·31	10
Patch Reef	0·7		27·54	1·55	2·45	0·021	11·02	76	37·57	13
Tobago	1·1		29·64	1·78	3·25	0·018	19·59	147	43·08	10

surface velocities (or slightly less when considering mean flow) and a roughness value of 0·05 based on grain size, k_{adm} was not found to be less than 100 υ/U, so the flow will be treated as rough. The equation for mean velocity in a rough-bed channel (Daily & Harleman, 1966) is

$$U/u^* = -5{\cdot}6\log k/h + 8{\cdot}2 \qquad (2)$$

where h is the depth, U is the mean flow, u^* is the shear velocity, and k is the bed roughness. To relate surface velocity u_s with mean velocity, the relationship derived by Southard *et al.* (1971) was used. By integrating the well-known velocity defect law for the outer region of a turbulent boundary layer over flow depth and setting $u = u_s$, the relationship between U and u_s was found to be

$$u_s - U = 2{\cdot}5\, u^*. \qquad (3)$$

Substituting Eq. (3) into Eq. (2),

$$u_s/u^* = -5{\cdot}6\log k/h + 10{\cdot}7. \qquad (4)$$

Once the critical shear stress τ_{cr} was estimated using the definition $u^* = \sqrt{(\tau_{cr}/\rho)}$, the Shields Criterion θ_t, dimensionless grain Reynolds number Re^* and Yalin parameter were calculated. Calculated u^* and Eq. (4) were used to estimate the velocity 100 cm above the bed, which is used in many comparisons.

One of the problems encountered during this study was the lack of available data on the density of various carbonate sediments. Although standard values of grain density for $CaCO_3$ range from 2·71 to 2·93 g cm^{-3}, for calcite and aragonite, respectively, Jell & Maxwell (1965) suggested densities ranging from 1·1 to 2·7 g cm^{-3} for specific skeletal fragment types. In a crude measure of sediment density, mass and displacement volume were determined for each of the relatively homogenous, well-sorted sediments. Additionally, where grains of *Halimeda* and the encrusting foraminifer *Homotrema* were large enough, densities of these individual components were also determined. Though simplistic, these methods were sufficient to reveal density contrasts within the carbonates and as compared to quartz.

RESULTS

The sieved grain-size distributions of the poorly sorted samples are shown in Fig. 2. Mean grain size, composition and approximated density of each sediment used in flume experiments are

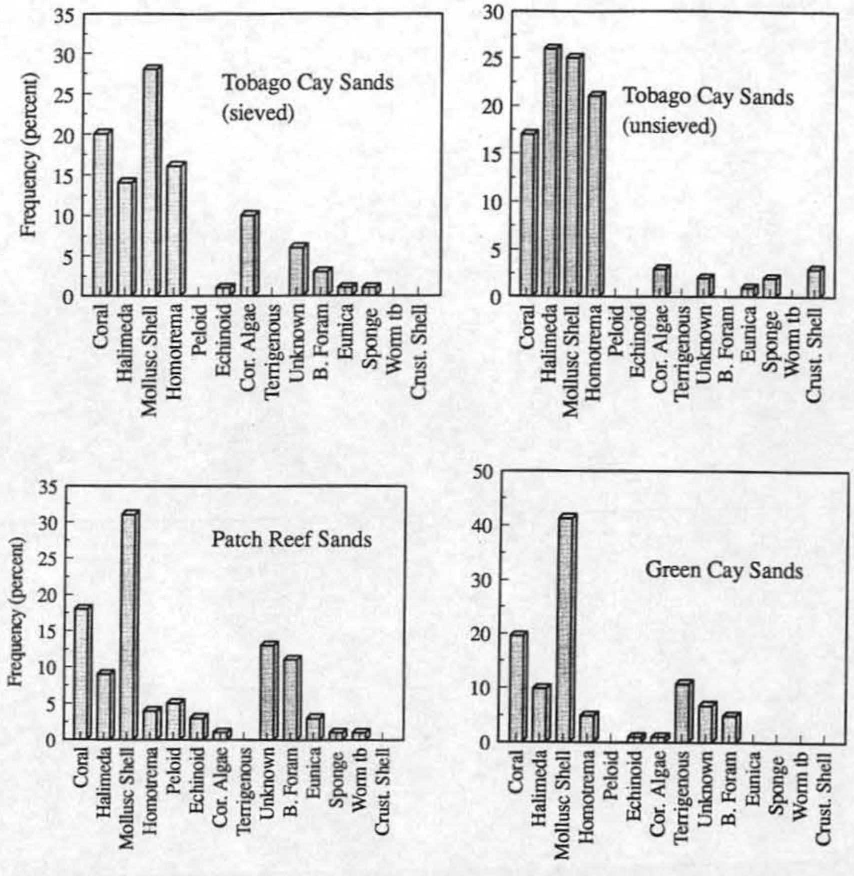

Fig. 3. Composition of carbonate sediments tested in flume experiments.

shown in Table 1 and Fig. 3. Also included in Table 1 are the results of flume experiments for each of the sediment samples. Values reported here are averages of 9–13 flume experiments, each of which met the conditions of minimal transport defined earlier. Minimal transport rates for each sediment type are shown in Fig. 4. Water temperature was ~20°C for all runs; consequently, values of $\nu = 0{\cdot}01\ \mathrm{cm^2\ s^{-1}}$ and $\rho = 1{\cdot}0\ \mathrm{g\ cm^{-3}}$ were used in calculations. The range of values for surface velocity and calculated shear velocity associated with the minimal transport rates is shown in Fig. 5. Data show a wider range of velocities associated with the threshold of transport for the mixed-size sediments (Patch Reef and Tobago Cay sands). Although Green Cay sands appear to require a slightly higher shear stress than the quartz and ooids of similar size, statistical analysis of the raw data using a Mann–Whitney test suggests that there are no significant differences among the data. However, data show a significant decrease in the shear velocity required to move platy, skeletal sands of a similar size (sieved Tobago Cay sample).

Two of the flume experiments were performed using sands of mixed size and composition, the Patch Reef and unsieved Tobago Cay sands. Mean grain size from sieve analysis was used as an estimate of roughness in all calculations. Observations of sediment movement and transport indicate that in both cases, particularly in the latter, the coarse fraction begins to move first. In the Tobago Cay sands sample, large grains of *Halimeda*, benthic foraminifer, and crustacean and mollusc shells, as well as unusually large chunks of *Homotrema*, were entrained before the finer-grained sediments. The smaller grains were not transported until the flow velocity was increased to the point at which scour and bedform development began.

DISCUSSION

The results of these experiments are comparable to previously measured data (Fig. 6), but the values for the threshold of transport appear slightly lower than those found by others. This difference may be due to how the threshold of transport is defined. Vanoni (1964) defined transport as negligible, small or critical and showed that in relation to the classic Shields curve, data

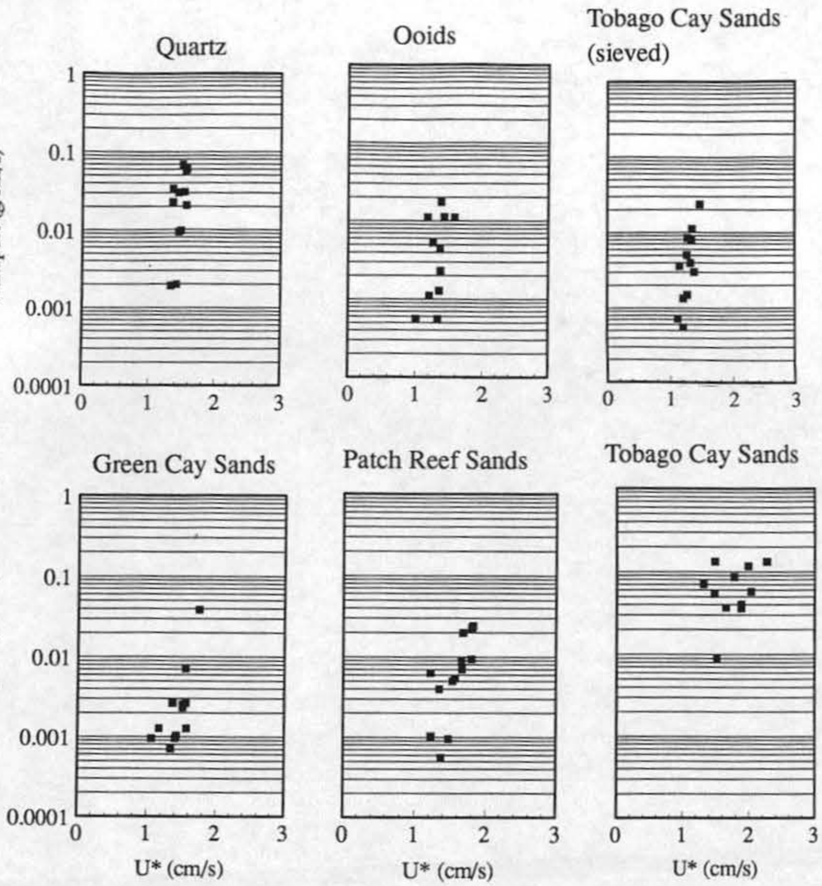

Fig. 4. Transport rates for each sediment type. Each data point is from a run which meets the defined threshold, where grain movement occurs, but significant bedforms or scour structures are not developed.

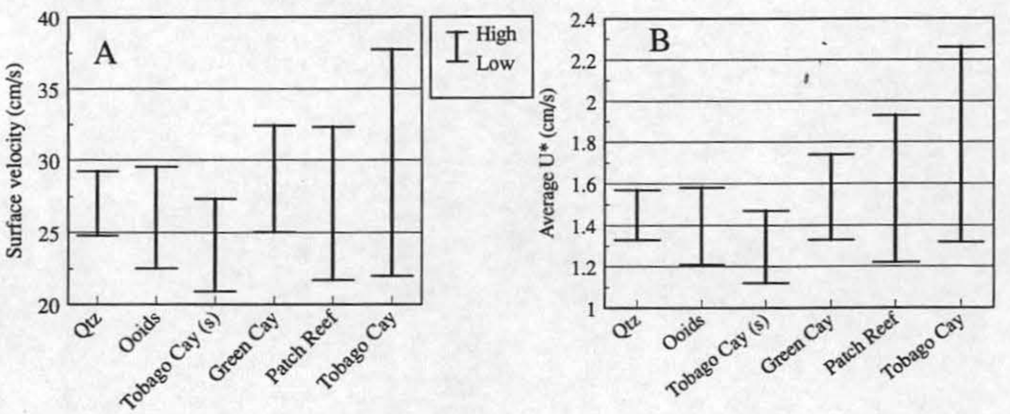

Fig. 5. Range of surface velocities (A) and calculated shear velocities (B) associated with transport thresholds in flume experiments: (s) refers to sieved sample.

plot well below what Shields defined as critical transport. Therefore, the values reported here may represent what Vanoni termed 'small transport'.

Statistical analyses of unaveraged data suggest that the transport threshold for both the ooids and Green Cay sands is similar to that of quartz sediments of the same size. Since the grains in these samples were relatively similar in shape and density to quartz grains, it is not surprising that their behaviour in fluid flow is similar.

In contrast, statistical analyses confirm that the sieved skeletal sands have a lower threshold of transport than the other sediments similar in size. This difference is a result of the platy nature of the grains and their lower density. These findings agree with those of Mantz (1977) as discussed earlier, whose study of mica flakes showed a reduced entrainment stress due to grain shape. As

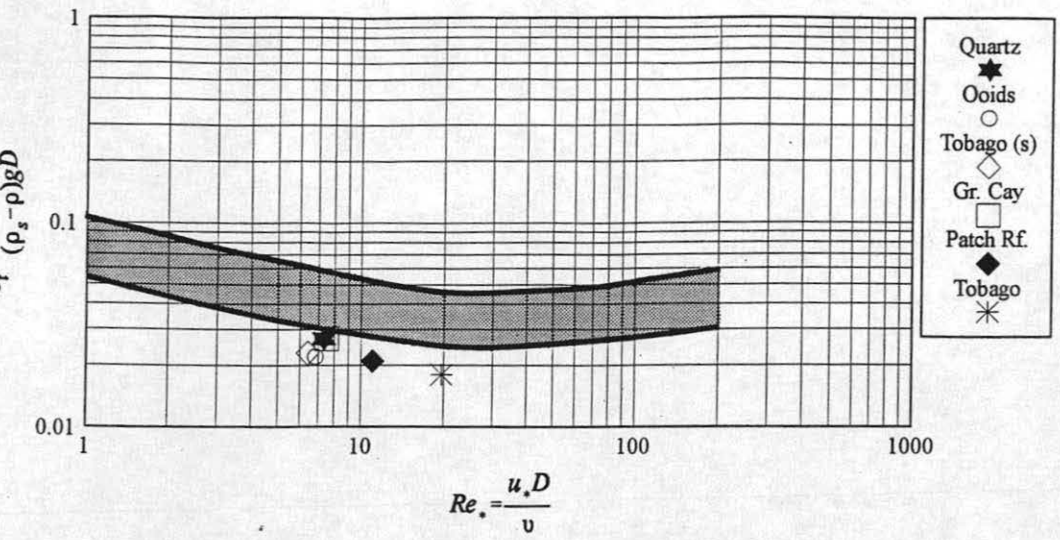

Fig. 6. Data from this study plotted on modified Shields curve. Sieved skeletal sands, poorly sorted Patch Reef sands, and the unsieved Tobago skeletal sands lie significantly below the conventional Shields curve.

grain size increases, density may depart more from the true mineral density due to natural porosity, pore filling and micritization. Therefore, the behaviour of carbonate sediments in fluid flow may depart more from that of quartz as grain size increases. Although sieving techniques do not necessarily sort particles hydraulically, in these experiments sieved sediments did not show differential transport or sorting under fluid flow.

Because of their heterogeneity in size, it was not appropriate to compare the Patch Reef sands and unsieved Tobago Cay sands with those discussed above. Given observations that the coarse component, particularly in the Tobago Cay sands, moves first, it is also not appropriate to use the mean grain size to predict initial motion. Additionally, because of the irregular nature of the sediment surface due to the heterogeneity of the poorly sorted sediments, the bed roughness factor may be greater than that represented by the mean grain size. However, calculations using an increased bottom roughness result in only a slightly higher shear stress associated with flow which produces entrainment.

In recent experiments, mixed-size siliciclastics were shown to exhibit a similar response to flow, with the coarse component moving prior to the finer grains (Li & Komar, 1992). Grain properties and boundary-layer dynamics can explain the initial movement of coarse-grained constituents. Research suggests that because coarse grains protrude higher into the flow and have a lower pivoting angle, they require lower entrainment stresses than if they were in a uniform bed (Wilcock, 1988; Li & Komar, 1992). Smaller grains within the mixture can also be hidden from flow and their motion impeded by the coarser components (Wilcock & Southard, 1988). Grain exposure may, however, be less important in sand than gravel, and the immersion of sand in a viscous sublayer may be more significant (Li & Komar, 1992). In summary, within poorly sorted sediments a complex boundary layer may exist where fine grains are not only physically trapped behind coarser grains, but also lie within a zone of lower shear stress on the bed. If a large proportion of irregularly shaped or lower-density large particles are present, the initial movement of the coarse component may be more pronounced.

Further research is needed to apply these findings to sedimentary deposits and depositional features found in both modern and ancient carbonate environments as well as those containing mixed siliciclastic and carbonate materials.

CONCLUSIONS

Our results show that the entrainment threshold for carbonate sediments is similar to that of quartz when grains are of similar size, shape and density. However, the lower density and platy or irregular shape of some skeletal sands reduces the velocity or shear stress required to initiate transport. In carbonate sediments of mixed size, coarse-grained particles may move prior to finer-grained materials. This phenomenon occurs owing to exposure and rollability of larger grains, and the establishment of a viscous sublayer which traps finer sediments in a zone of low-velocity flow. It is therefore possible to deposit and preserve fine-grained sediments under flow conditions traditionally thought to transport such materials.

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