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A Discussion and Classification of Subaqueous Mass-Transport with Particular Application to Grain-Flow, Slurry-Flow, and Fluxoturbidites

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ABSTRACT

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Sediments will remain at rest on the sea-floor provided forces of shear resistance exceed the downslope shear stress imposed by gravity The shear resistance of granular water-saturated sediments is discussed within the constraints imposed by the Coulomb model of shear failure, and the phenomena of thixotropy, liquefaction, retrogressive flow sliding and fluidization are discussed as mechanisms for producing the mass-mobilisation of sediment Processes of laminar mass-flow (= inertia flow) are broadly divided into those involving water as the interstitial fluid (grain-flow) and those having an interstitial fluid of enhanced viscosity (slurry-flow) Recent and experimental examples of inertia-flow are summarised and discussed under the headings grain-fall, grain-flow, slump-creep and fluxoturbidites It is concluded that grain-flow and slump-creep deposits may be more widespread in the sedimentary record than present reports indicate It is recommended that the term fluxoturbidite be restricted to its original sense, to describe the deposits of proximal turbidites in which the immediately pre-depositional transport was by inertia-flow A suggested terminology for subaqueous mass-transport processes and their products is summarised in the form of a flow-chart, terminological distinction being drawn between the processes of mobilisation, transport and deposition of the sediment, and between the various sedimentary beds or facies that result from emplacement by mass-transport

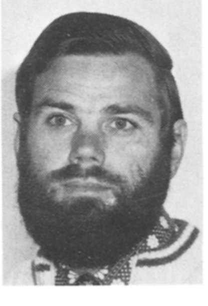
INTRODUCTION

The modern development of the theory of turbidity current flow (Daly, 1936) marks a highly significant moment in the history of sedimentology. Though their existence was initially controversial, turbidity currents are fairly readily reproduced in the laboratory (Kuenen, 1937), and experimental work has therefore allowed a theoretical understanding to be attained through the classic techniques of fluid dynamics (Kuenen, 1948; Kuenen and Migliorini, 1950, Middleton, 1970); "by about 1954, serious study shifted

from questioning the existence of turbidity currents to establishing their characteristics" (Menard, 1964).

Another important advance, but of a technological nature, was the development of the continuous seismic profiler (Smith, 1958), an accidental by-product of conventional echo-sounding bathymetric techniques (Veatch and Smith, 1939). This instrument for the first time allowed 'direct' observation of the major structure, distribution and thickness of sediments underlying the ocean floor. Use of the seismic profiler has resolved another long-standing controversy of sedimentary geology that of the nature and importance of down-slope slumping and sliding in marine situations. It is now clear (Heezen and Drake, 1963; Stanley, 1970; Lewis, 1971) that this process is volumetrically important in modern oceans, and that it may operate on slopes as low as 1°.

Between these two extreme types of sediment movement, i.e., between fully turbulent flow and elastic-plastic slumping or sliding, there exists a continuous spectrum of controversial processes to which the term subaqueous mass flow has been applied (Dott, 1963) In terms of dynamic analysis, both subaerial and subaqueous massflow lie on the boundary between fluid dynamics and rheology (Fisher, 1971). Until the recent work of Johnson and Hampton (1969), Johnson (1970) and Hampton (1972) on



Robert M. Carter was born and received his early education in England. Emigrating to New Zealand in 1956, he graduated BSc Hons in Geology from Otago University in 1963, returning to England to study for a PhD at Cambridge, completed in 1968. Whilst at Cambridge, he was fortunate in having his work on the functional morphology of bivalved mollusca supervised by Dr M.J.S. Rudwick.

Since 1968 Carter has been on the teaching staff of the Geology Department, Otago University, Dunedin, N.Z., during which time he has been interested in general problems of litho- and biofacies analysis, and particularly in the application of such data to palaeoenvironmental reconstructions. Besides his papers on mollusca, he has published on stratigraphic classification and on various aspects of New Zealand Cretaceo-Tertiary geology. During 1974—75 he is holding a Nuffield Foundation Travelling Fellowship at Oxford University, England.

debris-flows and slurry-flows, the only experimental works with direct application to geological mass-flow phenomena were those of Bagnold (1954, 1956), who was primarily concerned with the process of grain-flow *sensu lato*, and Metzner and Whitlock (1958), who summarised work on non-Newtonian dilatant behaviour in concentrated fine-grained suspensions

Many mass-flow phenomena involve the transport of a *dispersed solid phase* (e.g. large pebbles or fragments) in a *continuous fluid phase* (e.g. water, or mud-water slurry) (Holliday, 1966), and since this is a common industrial problem one might expect that hydraulic engineering literature would contain experimental data relevant to geological mass-flow processes. Unfortunately the kinetic complexity is such that "understanding of solid-liquid suspension flow in pipes is still quite limited" (Mih, 1972), and Babcock (1968) rather gloomily concludes that "hydraulic transportation is a commonplace mystery", and that "today we are still groping for the equivalent of Hooke's Law".

Thus there is an absence of comprehensive experimental data, and this has posed a substantial dilemma for the field geologist faced with the task of inferring depositional *process* from sedimentological *results* Having conceded, with Eldredge and Gould (1972), that purely objective documentation is logically impossible, the temptation is always to tailor field observations to presently *known* processes of sediment deposition, rather than to tie them to speculative theoretical possibilities; it is therefore not surprising that many published studies of flysch sequences place great emphasis on features explicable by the turbidity current hypothesis, and tend to be somewhat sceptical regarding deposition of individual beds by other mass-transport processes. However, a substantial number of writers (Crowell, 1957; Wood and Smith, 1957; Dzulynski et al , 1959; Dott, 1963, Peterson, 1965, Sanders, 1965; Scott, 1966; Stauffer, 1967; Fisher and Mattison, 1968, Jacka et al., 1968, Van Hoorn, 1969, Kelling and Woollands, 1969; Aalto and Dott, 1970; Fisher, 1971; Piper and Normark, 1971, Chipping, 1972, Lowe, 1972, Schlager and Schlager, 1973, Carter and Lindqvist, in press) remain unconvinced that the turbidity current mode of sediment emplacement plays the sole, or even major, part in deposition of proximal flysch facies, and all find substantial evidence for various types of mass-flow, particularly grain-flow *sensu lato*, other writers (e.g. Stanley, 1967, Walker, 1967; Wezel, 1968; Van Hoorn, 1969, Corbett, 1970) argue that the deposits in question, often 'fluxoturbidites' in the broad sense of Dzulynski et al. (1959), are mostly proximal turbidites, with Middleton (1970 p. 267) even concluding that "it is probable that the distinction between turbidity currents and grain-flows has been given too much prominence by some geologists". However, grain-flow undoubtedly exists as a process that is in at least some instances distinct from turbidity flow, and cannot thus be brushed aside, contrary to Middleton's suggestion, the development of field criteria by which the deposits of various mass-flow processes can be differentiated from turbidites, and from each other, is a most pressing need (cf. Stauffer, 1967, Walker, 1970).

This paper summarises some of the published experimental and field evidence for laminar mass-flow transport of sediment, particularly as relevant to grain-flow *sensu lato* It is therefore mainly derivative from the work of earlier authors, particularly building on the fundamental contributions to our understanding of mass-flow made by Terzaghi (1956) and Dott (1963), but it goes beyond these and other studies in making a clear terminological distinction between (1) the causal processes that initiate mass movement, (2) the actual mechanisms of mass transport, and (3) the depositional results of mass transport (cf. Walton, 1967, Cooke et al , 1972).

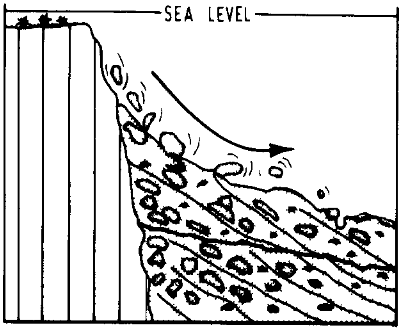
I A SUMMARY OF SOME SUBAQUEOUS MASS-TRANSPORT PHENOMENA

Historical nomenclature

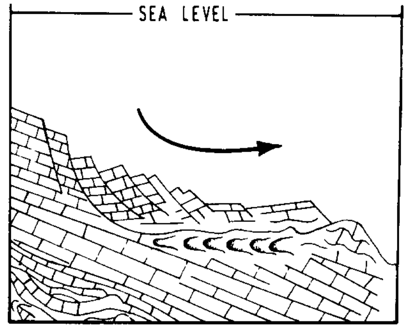
As traditionally used in geology, the term mass-transport collectively describes a number of subaerial processes by which erosion products are bodily removed down slope by gravity, the processes contrast with those of the fluvial regime, where running water forms the actual transporting medium, but water may be involved in lubricating, or diluting, mass-flow sediments Subaerial mass-transport processes range from rock-fall at one extreme, through various intermediate processes to highly fluid debris-flows at the other. Historically important contributions to the understanding of mass-transport have been made by Jones (1937), Terzaghi (1943, 1955, 1956), Crowell (1957) and Dott (1963). The latter paper, in particular, provided the first major classification of subaqueous mass movements, and stressed that there was a continuum of processes that link "subaqueous gliding and plastic mass flow to turbid, viscous fluid flow", viz. subaqueous mass-transport processes (see Fig 1)

During the 1950's, following the suggestion of Kuenen and Migliorini (1950) that many flysch-type sediments were best explained as turbidites, the turbidity current mechanism found wide applicability in sedimentary geology. The sequence of sediments deposited from a single turbidity current was generalised by Bouma (1962) into a turbidite facies model, now called the Bouma sequence This conceptual break-through opened the way for detailed studies of a variety of ancient flysch sediments (see Walker, 1970, for summary and references). Several workers, especially those studying the proximal part of a series of turbidites, encountered evidence for mass-transport that did not fit the Bouma turbidite model closely, and hence the terms *fluxoturbidite* (Kuenen, 1958; Dzulynski et al., 1959) and *grain-flow* (Bagnold, 1956, Dzulynski and Sanders, 1962; Sanders, 1965, Stauffer, 1967) became established.

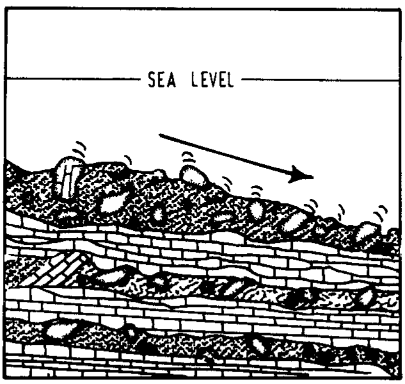
At about the same time, engineering geologists were devoting increasing attention to the problems caused by subaerial landslides, and several comprehensive treatments of the cause and nature of landslides were published (Sharpe, 1938, Ecker, 1958, Zaruba and Mencl, 1969). These contributions,



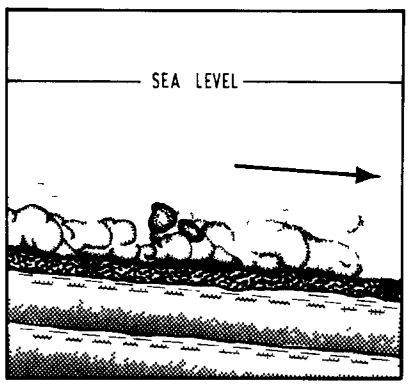
SUBMARINE ROCKFALL
(transport distance short across steep slopes)
Rolling or freefall of individual clasts
Sand to boulder sized clasts, poor sorting
Depositional units often without distinct boundaries
Bedding crude-absent, depositional packets often markedly uncomformable with each other
Deposition at angle of granular stability.



SUBMARINE SLIDES OR SLUMPS
(transport distance and slope variable)
Displacement of stratigraphic units
Movement along discrete shear planes
Little or no internal flow
Intra-slide folds and faults



SUBMARINE INERTIA FLOW
(transport distance intermediate across moderate slopes)
Large volumes of mud to boulder-sized material moving together
Depositional units show distinct boundaries
Planar base and top or planar base and hummocky top
Poor sorting, normal grading rare, reverse grading sometimes present
Mud (slurry-flow) or sand (grain-flow) matrix
Clasts supported by matrix, sometimes oriented parallel to bedding
Deposition by freezing



SUBMARINE TURBIDITY FLOW
(transport distance far across gentle slopes)
Large volumes of muddy to granular (?cobbly) material moving together
Depositional units usually show distinct boundaries.
Erosive base often sole-marked, top gradational to inter turbidite hemipelagites
Variable sorting, normal grading, Bouma sequence typical
Clasts supported by fluid during movement
Deposition by fallout from turbulent suspension (with basal shear fluxoturbidite).

Fig 1 The spectrum of submarine mass-transport processes (after Dott, 1963, Cooke et al, 1972)

together with the more theoretical papers of Terzaghi (1956), Reynolds (1954), and Andresen and Bjerrum (1967), stressed the importance of the change of state of the sediment at the time of mobilisation, and the processes of liquefaction, thixotropy and fluidization were suggested as explanations for specific mass-flow phenomena

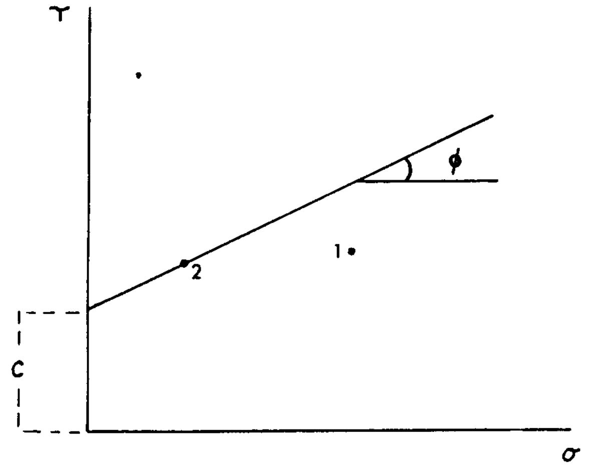
Mass-transport mobilization

As discussed by many previous writers (e g. Terzaghi, 1956, Shepard and Dill, 1966, p. 298), sediments will remain at rest on the sea-floor provided the combined forces of shear resistance are greater than the shear stress imposed by gravitational acceleration (Fig. 2) The shear strength of granular materials is usually calculated from the Coulomb model of shear failure. Though it is not the only failure theory used in soil mechanics, the Coulomb model has been found widely applicable to water-saturated granular material, and at its simplest states that the shear strength of a material is a linear function of the normal stress applied viz. $S = C + \sigma \tan \phi$, where S is shear strength; C is the interparticle force due to cohesion, σ is normal stress, and ϕ is termed the angle of internal friction, whose tangent represents the gradient of the line defining the failure envelope on a shear stress/normal stress graph (cf Fig 2a) (It should be stressed that C and ϕ are material properties that require empirical determination for a given sediment. When treated as cohesionless materials, the value of ϕ for coarse silts to sands is determined to be in the range of 28—42°. ϕ generally increases with the density of the material (implying closer packing), and for a given density it also increases with both sorting and grain angularity — Wu, 1966) In the case of water saturated sediment, the normal stress may be diminished by an amount equal to that of any excess pore water pressure that exists, thus for a potential shear plane within a pile of water saturated sediment, the Coulomb equation is generally written (after Terzaghi, 1956)· $S = C + (\gamma_s Z - u_w) \tan \phi$, where γ_s is the submerged unit weight of the sediment, Z the depth below the free surface of the sediment, and u_w the excess pore water pressure at the point of stress.

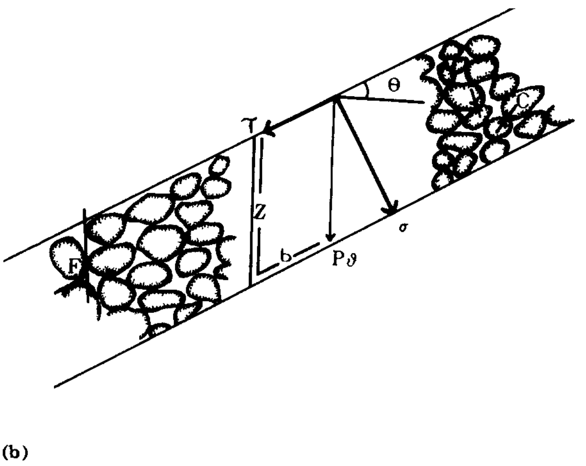
The applied shear force to a potential shear plane within the sediment pile is merely the downslope component of gravitational force (Fig 2b), or $T = P_v \sin \theta$, where θ is the angle of slope on which the sediment rests, and P_v the applied gravitational force (= $\gamma_s Z$ at depth within the sediment pile) Failure of the sediment pile will occur if the shearing resistance S is decreased below the applied shear force in any of the following ways

(1) By thixotropic change in cohesive properties consequent upon an applied shock (e g. earthquake), such behaviour is generally only associated with muddy sediments, but muds are commonly interstratified with other lithologies which may thus become involved in mass movements consequent upon thixotropic changes (cf. Crowell, 1957).

(2) If the sediment initially accumulated with metastable grain packing



(a)



(b)

Fig 2 (a) Graphical representation of the Coulomb model of shear strength for granular materials Combinations of shear (ordinate) and normal (abscissa) stresses that plot below the linear strength function, such as point *1*, represent stable situations, whereas points on the line, such as point *2*, represent incipient failure of the material Since stresses that plot above the line cannot be sustained in this material, the line defines the limiting stresses and is often called the failure envelope Material properties defined by the strength function are the cohesion (c, equal to the intercept of the line on the ordinate) and the angle of internal friction (ϕ, whose tangent equals the slope of the line)
(b) Vector representation of the Terzaghi model for shear strength in a granular material The sediment will remain at rest on a sea-floor of slope θ provided the shear resistance is greater than the applied shear stress (see text for detailed explanation) (after Terzaghi, 1956 and Shepard and Dill, 1966)

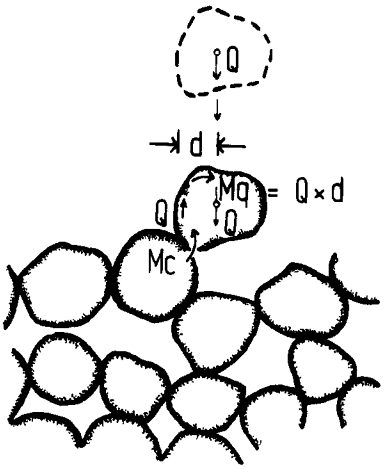


Fig 3 Diagrammatic representation of metastable grain packing in water saturated sediments (after Terzaghi, 1956) When a sinking particle weight Q arrives at the sediment surface, it tends to roll into a stable position as a result of an overturning couple, $Mq = Q \; d$ Mq decreases in inverse proportion to the fourth power of the diameter of the grain, whereas the resisting couple, Mc, produced by adhesion at the point of impact, is independent of grainsize The probability of settling particles assuming stable positions therefore decreases with decreasing grainsize

(Fig 3), an applied shock may result in collapse of this packing and the temporary production of excess pore-water pressures, direct mobilisation by liquefaction follows (Terzaghi, 1925). Such behaviour is most often associated with sediments in the very fine sand to silt range (Terzaghi, 1956, Shepard, and Dill, 1966), though some experimental evidence suggests that it may occur in loose cohesionless grains of any size as an intermediate step in the process of consolidation (Florin and Ivanov, 1961, Hendry, 1973). Empirical calculations (Morgenstern, 1966, Van der Knaap and Eijpe, 1969, Middleton, 1970) suggest that the excess pore pressures associated with liquefaction may persist long enough (a few minutes to several hours) for appreciable sediment transport to take place, over at least several kilometers

(3) By oversteepening of the sedimentary pile, due to undercutting by waves or currents, or to mass-failure further down-slope (retrogressive flow slide — Andresen and Bjerrum, 1967).

(4) An upward flow of fluid through the sediment may produce a continuing excess pore-water pressure, mobilisation is by fluidization (Reynolds, 1954).

(5) The slope the sediment rests on is increased, or more sediment is added above (cf. Allen, 1965), both processes will act to increase the effective shear stress, and the former will also decrease the effective normal force and hence the shear strength.

Processes 2 and 4 above, both involving excess pore pressures, are often

discussed with respect to mass-flow of sand The phenomenon of liquefaction was termed *Setzungsfliessung* (subsidence flow) by Terzaghi (1925), when he suggested for the first time that temporary excess pore pressures might be generated by the collapse of initially metastable sediments. The term spontaneous liquefaction was only adopted later, but has since become widely used in engineering literature (e g Andresen and Bjerrum, 1967) It is important to appreciate that use of the term liquefication does not imply Newtonian fluid behaviour during transport (cf. *Mass-transport* below).

The applications of fluidization in geology have generally been limited to igneous phenomena such as intrusive pipes (Reynolds, 1954) or ash flows (Sylvester-Bradley, 1967) and the requirement of a continuing supply of fluid to maintain the excess pore pressures may suggest that the process is unimportant in conventional sedimentology However, continuing excess pore pressures are locally produced by sedimentary loading (cf. Fisk et al., 1954), or by hydraulic effects consequent upon rapid or extreme tidal changes (cf Terzaghi, 1956). It would therefore be unwise to dismiss fluidization altogether from the list of processes of potential sedimentologic importance, particularly as some recent writers predict or report such a close relationship between the processes of liquefaction and fluidization that the distinction may be nominal (cf Hendry, 1973, Carter, 1975)

Mass-transport sensu stricto

During free-fall, clastic grains behave in an essentially elastic manner (Dott, 1963); during transport by turbidity currents, "there is no slip between the fluid and the grains, the grains are in effect prisoners of the flow and are passive within it" (Sanders, 1965, p 194), and the current may be treated as a viscous Newtonian liquid, subject to the laws of fluid dynamics. If sediment failure takes place along a discrete shear plane, as in the case of slides and slumps, then behaviour is elastic-plastic, i.e., shear deformation is entirely confined to a narrow plastically-deforming layer at the sole of the sheet, and the overlying block is carried as an intact, elastic mass (Dott, 1963). Establishing the physical state of other forms of mass-transport, especially grain-flows, is unfortunately not so straight forward. However, recent experimental work (particularly that of Johnson and Hampton, 1969) suggests that the rheology of moving grain-flows and debris-flows is most closely approximated by Bingham or pseudo-plastic models (cf *The rheology of mass-transport*, p 155)

Widespread application of the concept of grain-flow in geology initially arose out of Bagnold's (1954) experiments to investigate the properties of concentrations of cohesionless grains in a Newtonian fluid under shear. The fundamental discovery resulted that such systems "exhibit properties in mass that cannot be predicted from analysis of the behaviour in fluids of single isolated grains" (Sanders, 1965), in particular, a force called the dispersive pressure, was shown to be exerted normal to the mean flow direction and to

be "of such a magnitude that an appreciable part of the moving grains is in equilibrium between it and the force of gravity" (Bagnold, 1954, pp 49—50). The dispersive pressure comprises a component due to intergranular collisions, *and* a component due to statistically ordered shear velocity changes as one grain passes near another. At high flow rates, low viscosities or for large grain sizes, the grain collision effect predominates and shear is said to be in the grain inertia region (or regime), at low flow rates, high viscosities or for small grain sizes, the effects of fluid viscosity dominate and shear is said to be in the viscous region. Bagnold applied his discovery of dispersive pressure to the first analytic description of the flow of dry sand on a slope exceeding the angle of stable repose, and it became apparent that geologists could add a third distinctive type of grain transport to the already established traction and turbidity current processes

The term *grain-flow* was not used in Bagnold's 1954 study, only appearing later (1956, p 239). Since then the term has had a complex history, with some writers using it in a general, almost vernacular, sense, and others attempting to define it more closely (see Fig. 4) Sanders (1965) discussed grain-flow in the bed-load carpet of turbidites in some detail, using the term *inertia flow* for "transportation of sediment in which grains move above the bottom but are not supported by upward components of the turbulent movements within the fluid" (p 329). This usage was later criticised by Middleton (1970, p 264), on the grounds that as so defined, inertia flow may involve grain-flow in both the inertial and viscous regions of Bagnold However, confusion equally stems from Bagnold's original use of the term 'grain-flow' to encompass flow in his viscous region, in which the behaviour of the flow is dominated by the effects of the viscosity of the continuous phase rather than being solely a product of the dispersed solids present. Since in any natural example the enhanced viscosity of the continuous phase will result from its being a clay—water slurry (which may, or may not, behave in Newtonian fashion), the term *slurry-flow* seems more appropriate for mass-flows that are moving in the viscous region (If there are objections to the application of the term slurry-flow to those of Bagnold's experiments

<table>
<tr><th colspan="2">BAGNOLD (1954 '56)</th><th colspan="2">SANDERS (1965)</th><th>STAUFFER (1967)</th><th colspan="2">MIDDLETON (1969 70)</th><th colspan="2">THIS PAPER</th></tr>
<tr><td>INERTIAL REGION</td><td rowspan="2">GRAIN FLOW</td><td>INERTIA FLOW (as discussed)</td><td rowspan="2">INERTIA FLOW (as defined)</td><td>GRAIN - FLOW</td><td>INERTIAL REGIME</td><td rowspan="2">GRAIN FLOW</td><td>GRAIN - FLOW *sensu stricto*</td><td rowspan="2">INERTIA FLOW</td></tr>
<tr><td>VISCOUS REGION</td><td>VISCOUS SUSPENSION</td><td>SEDIMENT FLOW</td><td>VISCOUS REGIME</td><td>SLURRY-FLOW</td></tr>
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Fig 4 Previous usages of grain-flow and related terms (see text for full discussion)

in which the continuous phase was by intention a Newtonian fluid, albeit very viscous, then the experiments may alternatively be described as inertia-flows that were sustained by viscous dispersive pressure — see also discussion under *The rheology of mass-transport*, below).

Thus, following Bagnold (1954, 1956), two theoretically different types of behaviour are likely to be characteristic of mass-transport in which deformation takes place by laminar shear

(1) Where the continuous phase has a low viscosity, i e , generally when it is water, the dispersive pressure generated will result from actual impacts between grains of the dispersed phase, the continuous phase has no strength and deforms as a Newtonian fluid This is grain-flow *sensu stricto*, or grain-flow in the inertial region of Bagnold, it is referred to simply as grain-flow (*sensu stricto* implied) in this paper.

(2) Where the continuous phase has a high viscosity, i.e., generally when it is a mud—water mixture, or slurry, the dispersive pressure generated will result from ordered shear-velocity changes as dispersed grains approach one another (Bagnold, 1954), and a further dilatant effect introduced by non-Newtonian behaviour of the fine-grained clay suspension (Metzner and Whitlock, 1958). This is grain-flow in the viscous region of Bagnold (and Middleton, 1970), though grain-flow is a somewhat unhappy description of the process, and slurry-flow has been preferred here.

Stauffer (1967), following Bagnold (1956), defined the term grain-flow to cover a very large range of phenomena, including particularly processes where discrete clasts are suspended in a highly viscous muddy matrix and form mud-flows or debris-flows in the usual sense of the word (Johnson, 1970). It is quite clear that such usages, and specifically the definitions of grain-flow in Stauffer (1967) and Middleton (1970), encompass a wide range of mass-transport phenomena, yet to the field geologist the term grain-flow usually implies a process approaching grain-flow in the inertial region of Bagnold

Sanders' term inertia-flow (Sanders, 1965), as originally defined, encompasses both grain-flow and slurry-flow as discussed above It is thus a useful term, since it stresses that the laminar nature of transport stems from the inertia of the constituent sediments, but it does not specify whether the dispersive pressure generated is due mainly to interactions between unimodal granular material (grain-flow), or to the high viscosity of the continuous fluid phase (slurry-flow), or to both. Therefore, and whilst admitting Middleton's (1970) criticism, the term inertia-flow is provisionally retained as an extremely useful term of ignorance, at least in so far as its geologic products are presently not easily subdivided into those more strictly deposited by grain-flow and slurry-flow respectively

The rheology of mass-transport

Field observations

Many previous writers have commented on the fact that subaerial mass-

flows transport large and often fragile clasts for great distances, and every field geologist has had the experience of finding isolated pebbles or boulders contained in a generally sand-sized bed of redeposited sediment. That such relatively large clasts may be carried great distances requires the presence of a force, or forces, that keeps the clasts in suspension during transport In the case of proximal turbidites, the force may be attributed to upward components of fluid turbulence during transport, but recent field observations suggest that laminar flow is typical of the denser types of mass-flow (typified by subaerial debris-flow, e.g Johnson, 1970), and that fluid turbulence therefore cannot be the cause of the suspension of large clasts

A number of different mechanisms have been described whereby clasts might remain suspended in mass-flows, they include suspension due to Bernoulli's principle (Fisher and Mattinson, 1968), to drifting of clasts into zones with the least rate of shear (Sanders, 1965), to enhanced buoyancy caused by the density of the continuous fluid phase (Johnson, 1970), to viscous and inertial dispersive pressures caused by the dispersed clasts themselves (Bagnold, 1954), to clay dilatancy (Metzner and Whitlock, 1958), and to a finite yield strength in the continuous phase slurry (Johnson, 1970). It is possible, if not likely, that all of these effects may play a part in suspending clasts in some viscous mass-flows, but most recent writers have argued that buoyancy and the finite yield strength of the continuous phase are the most important factors bearing on the suspension of large clasts in viscous mass-flows (e.g Middleton and Hampton, 1973).

Rheologic models

Developing a rheologic model that approximates the behaviour of natural mass-flows is a difficult procedure, not least because of the spectrum of different processes and materials that may be involved in specific mass-flows, or even in the same mass-flow at different times (an illuminating discussion on the general problem of choosing between competing rheologic models may be found in Johnson, 1970, pp. 517—519). For instance, Booth and Self (1973) have shown that lava flows approximate a Newtonian fluid model near the eruptive vent, but find a Bingham plastic model more appropriate to describe their behaviour elsewhere; and where Glen (1952) assumed a pseudoplastic model for the deformation of ice in a moving glacier, Meier (1960) preferred a Bingham model involving a definite yield strength.

Johnson and Hampton (1969) and Johnson (1970) have recently described the results of laboratory experiments with various viscous mass-flows for which they found a 'Coulomb-viscous' model most appropriate The model has the form

$$T = c + \sigma_n \tan \phi + n\epsilon$$

where $T > c + \sigma_n \tan \phi$, T is internal shear stress, σ_n internal normal stress, ϕ

(the angle of internal friction) is viscosity, and ϵ is rate of shear strain. The model plots in Bingham fashion on a stress/rate-of-strain graph, with the yield strength having components due to cohesion and intergranular friction Application of the Johnson model leads to the conclusion that for material flowing in channels, regions will exist where the applied shear stress is less than the strength of the material In particular, a moving debris flow is hypothesized to travel mainly by laminar shear within a circumferential zone where shear strength had been exceeded, and to carry with it a rigid plug in the top centre of the flow where shear strength has not been exceeded (Fig. 5). Movement is believed to commence by shear along the boundary surface where the flowing material is in contact with its substrate, but only after a critical thickness of material has accummulated If the flow is fed from behind, the boundary surface may increase in width to become a peripheral zone within which all shear deformation is taking place, with a plug of material passively rafted above it (Fig 5b,c). In the case of sub-aqueous mass-flows, the overlying water column will exert a reverse shear stress on the top of the flow, and the plug therefore might float below the flow-surface (Fig 5d,e). As the flow travels further from source, or as the amount of material fed into it decreases, the thickness diminishes to that critical value at which the thickness of the plug equals the thickness of the flow, and the material freezes *in situ*

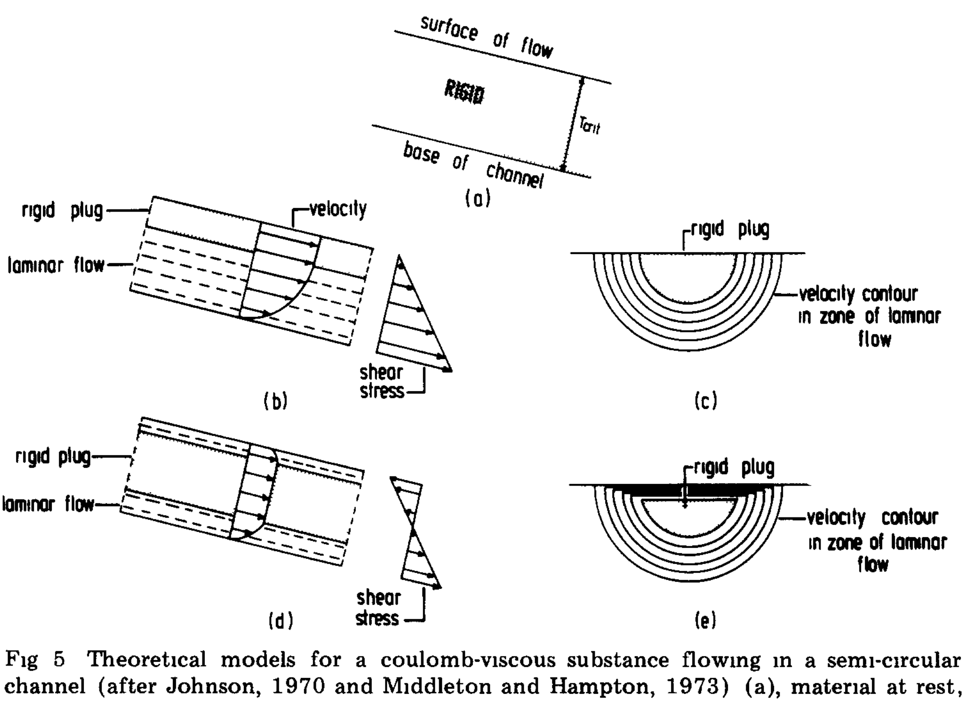

Fig 5 Theoretical models for a coulomb-viscous substance flowing in a semi-circular channel (after Johnson, 1970 and Middleton and Hampton, 1973) (a), material at rest, (b) and (c), material moving subaerially by plug-flow, (d) and (e), material moving sub-aqueously by plug-flow (see text for detailed explanation)

Laboratory observations on mass-flows, including both debris-flows, slurry-flows and grain-flows (Johnson and Hampton, 1969, Johnson, 1970; Hampton, 1972) suggest that the Johnson model of Coulomb-viscous plug flow may appropriately describe all these processes, and Johnson (1970) further extends the model to the description of flowing ice and lava. However, and as Johnson himself points out (1970, p. 517), many of the features of viscous mass-flows are equally well explained by a pseudoplastic model as they are by a Coulomb-viscous model. It therefore behoves us to act with great caution when applying the laboratory findings to the field situation, and to be particularly careful that our field nomenclature does not require us to make rheologic inferences that are beyond present knowledge or techniques.

Nomenclature

The division of inertia-flows into grain-flows (grain impact dispersive pressure) and slurry-flows (viscous dispersive pressure) directly follows the experimental work of Bagnold (1954, 1956), although Bagnold's viscous dispersive pressure was exerted by a viscous fluid of effectively Newtonian properties (glycerine). In view of the widespread industrial use of *slurry* to imply a fluid mixture of mud grade fines and water, and in view of the fact that such slurries are the only obvious means by which naturally occurring mass-flows can come to possess enhanced viscosities, it seems sensible to use the term slurry-flow as a general description of the transport process inferred to operate in the majority of viscous mass-flows.

Since a slurry has an enhanced viscosity, a viscous dispersive pressure (in the Bagnold sense) will be exerted on any larger detritus that the slurry carries The experiments reported by Johnson (1970) and Hampton (1972) on kaolin—sand—water slurries suggest that such slurries possess strength as well as enhanced viscosity, and that they therefore move by Coulomb-viscous plug-flow It seems probable that every gradation exists between the two extremes of (1) highly viscous sticky slurries that move by Coulomb-viscous plug-flow, and (2) highly fluid watery slurries whose yield strength approaches zero and which move by pseudoplastic laminar flow where shear is distributed throughout the flow thickness. Field observations of debris-flows (Johnson, 1970) and sand flows (Carter, 1975) suggest that such a gradation of flow behaviour may even exist consecutively within a single flow, and it would seem unwise to use a terminology that distinguished between these processes. It is therefore suggested that the term slurry-flow appropriately covers the whole flow spectrum, with the proviso that whereas the Coulomb-viscous rheologic model may be appropriate to more viscous mass-flows, a pseudoplastic model may better fit the behaviour of more fluid slurries.

In view of the widespread usage of the term 'debris-flow' for slurry-flows that contain an appreciable content of suspended clasts, use of the term in a restricted sense (as suggested by Hampton, 1972) to apply to the theoretical

transport *process* operative in a slurry-flow, irrespective of whether any macroscopic 'debris' is involved, seems unwise, and is not followed here

Deposition from mass-transport

Whatever the precise mode of transport within a mass-flow, it seems likely that final deposition of the sediments is by freezing *in situ*, sometimes with accompanying sediment shear (Stauffer, 1967, Middleton, 1970) The only experimental description of such a process is that of Middleton (1970), but whether this description is applicable to deposition from all mass-flows is not known. This remains one of the many areas in which more detailed laboratory work is required

At least two slightly different models of 'freezing' on deposition of a mass-flow can be imagined

(1) Where the bed is expanded into a quick state by intra-flow dispersive pressure, and collapses to the grain-bed when this dispersive pressure falls below gravitational forces (see quotation from Middleton on p 168) Deposition is effectively simultaneous throughout the bed.

(2) Where a surface separating stationary from moving particles moves rapidly up through the flow as transport ceases, deposition is therefore not simultaneous throughout the bed. If the depositional surface migrates upwards gradually, a comparatively homogeneous bed might be expected If the depositional surface migrates up more spasmodically, corresponding to inhomogeneities within the flow, then the bed might consist of several superposed subunits, each sub-unit would be bounded below by a plane at which the upward migrating depositional surface paused briefly while transport continued in the sediments above. The process would be analogous to that suggested by Sanders (1965), whereby a basal flowing-grain layer "shears out" from under a turbidity current, only in this case it is successively higher parts of a moving inertia-flow that "shear out" from *over* the earlier deposited parts of the same flow. Such a depositional mechanism might result in composite beds analogous to those described from proximal turbidites (cf Hendry, 1973), and at least some published figures of composite inertia-flows could be interpreted in this way (e.g. Fisher, 1971).

Though we may be unsure of the precise mechanism operating when a mass-flow "freezes", Middleton's experiments demonstrate that the process is fundamentally distinct from deposition by traction, or by traction with fallout, characteristic of normal bottom currents and of turbidity currents respectively Deposition by freezing should therefore leave distinctive traces of its operation on the sedimentary product. These traces include reverse grading (Fisher, 1971), isolated large clasts that are passively rafted within the flow (Johnson, 1970) and oriented parallel to bedding (Fisher, 1970), and the presence of a pervasive lamination due to sediment shear during the final stages of deposition (Stauffer, 1967). Though all of these textural phenomena can also be produced by processes other than mass-flow (e.g.

tillites contain isolated large clasts, alluvial deposits may contain reverse graded sequences; and fluxoturbidites may contain shear lamination), together they comprise a distinctive assemblage of textural criteria by which inertia-flow deposits can be recognized It is to be hoped that further experimental and field studies will result in additional, and perhaps more specific, criteria by which mass flow deposits can be differentiated from other similar sediments.

II RECENT EXAMPLES OF INERTIA-FLOW

Numerous field and some laboratory observations of various types of inertia-flow occur scattered through the literature on Recent sedimentation. Inertia-flow apparently occurs most often in and around the head of steep-sided submarine depressions, on oversteepened depositional slopes such as the advancing front of a delta, in any situation where sediment of suitable grain-size characteristics has been deposited metastably, and during the early depositional stages of particularly dense turbidity currents. As a process, inertia-flow occupies an intermediate position on the spectrum of mass-transport processes (cf Fig 1). Natural occurrences of some of these processes are further documented below, under the headings *Grain-fall*, *Grain-flow*, *Slump-creep* and *Fluxoturbidites*

Grain-fall

When sediment of any grain-size is transported to the edge of a slope considerably in excess of its stable angle of repose, the individual grains pass into free-fall under the direct influence of gravity. In the ideal case, the grains have no effect on each other, but fall individually at a rate determined by their size, density, surface roughness and by the viscosity of the ambient medium (The principle is well known through its application in grain-size analysis techniques involving a settling column.) In more realistic natural situations, the particles fall and bounce down steep slopes, interacting with each other and with the bedrock or talus deposits over which they are passing. Such free-fall deposits usually accumulate as fans at the foot of the slope, and both the processes of transport and their geomorphic products have been studied in some detail by modern geomorphologists (e.g see references in Carson and Kirkby, 1972) It has been suggested that in some cases a highly concentrated subaerial rockfall may generate sufficient kinetic energy to become fluidized, with ensuing transport of the debris over a wide region at the foot of the slope (Kent, 1966). The higher viscosity of the medium, with a consequently much reduced terminal velocity for a free-falling particle, make fluidization unlikely in subaqueous environments, even assuming it is theoretically feasible at all (Shreve, 1968).

Free-falling particles in the sand grain-sizes were first reported in the subaqueous environment in 1959 by a Scripps Institute of Oceanography

SCUBA party, who observed "sand falls where flowing sand spilled over abrupt drop-offs in the axis of side tributaries cut in the upper lip of the main channel of San Lucas canyon" (Dill, 1966, p. 763). The sand is moved to the lip of the canyon by normal near-shore traction current processes, particularly during periods of enhanced bottom current activity associated with heavy storm swells. The process has been photographed in action (e g Dill, 1966, fig. 4), and a large number of published bottom photographs from all depths show that sand accumulates as "perched" lenses wherever ledges and shelves are associated with steep slopes Sand in this position could only have been emplaced by free-fall, and the ubiquity of the process is demonstrated by examples from the sides of submarine canyons (Dill, 1964, figs 3 9 and 3.11), sea-mounts (Heezen and Hollister, 1971, fig 12.19), and deep-sea trenches (Heezen and Hollister, 1971, fig 11 9) Submarine rock-falls involving larger sized clasts are also common in similar environments (e.g Hersey, 1967, figs 11.3—4, 11.6, 11 11, 13.11, 17.26, Heezen and Hollister, 1971, figs, 8.11, 11.1 (left), 11 36, 13 17)

Grain-flow sensu stricto

"When dry sand of fairly uniform size is supplied at the top of a slope of the same sand inclined at an angle very near that of collapse, the supplied sand moves down the slope as a flow, i.e., every grain moves relatively to its neighbours and the shearing is general. The moving mass can be distorted round obstacles placed in its path The flow has a well-defined front and advances at a constant speed depending only on the grain size and the depth of the flow. This phenomenon can be seen on any steep dune slope" (Bagnold, 1954, p 61).

As so described, grain-flow also occurs in the subaqueous environment (see Allen, 1965). It specifically operates in the absence of a fine-grained 'lubricating' phase (cf the importance of mud, even in small amounts, in slurry-flow), and the flowing part of the sediment is therefore of broadly unimodal nature, though blocks larger than the mode are commonly carried passively in a grain-flow. There are also grain-size limitations Because of area to volume relationships, and the consequent predominance of interparticle surface forces, grains finer than coarse silt generally will not flow independently of a viscous transporting medium At the other end of the spectrum, grain-flow is rarely inferred for deposits with clasts greater than about 10—20-cm mean diameter. This limit seems more likely to be of empirical than theoretical nature Given a source of moderately rounded and sorted clasts, and a suitable mobilisation factor, grain-flow would presumably occur in clasts of virtually any mean size. In fact, the general nature of weathering and transport processes is such that 10—20-cm gravels represent the maximum grain size at which moderately sorted and rounded, broadly unimodal, sediments commonly occur.

The preceding discussion tacitly assumes that the grain-flow referred to is

taking place in the inertial region of Bagnold, i e., that actual grain to grain contacts predominate in the momentum-transfer process. For a given grain-size, increasing amounts of mud mixed with the continuous phase will result in a change of behaviour; flow moves to the viscous region of Bagnold, and approximates the process we have earlier termed slurry-flow. Johnson and Hampton (1969), Johnson (1970) and Hampton (1970) have shown that as little as 10% mud mixed in with the continuous phase is sufficient to move flow into the viscous region. It could perhaps be argued, therefore, that virtually all natural deposits will result from slurry-flow processes, but reported field observations demonstrate that there is a complete spectrum of processes, and depositional products, between these two extremes True inertial grain-flow is known to be particularly important in proximal environments in submarine canyons, in sands that are derived directly from the surf-zone and therefore have no appreciable mud content.

Like sand-falls, subaqueous sand-flow was first directly observed in 1959 by SCUBA equipped scientists from Scripps in the canyons off Baja, California (Dill, 1966, p. 763), and has since been described in detail in both the San Lucas Canyon and the Scripps Canyon off La Jolla. "During storm conditions, sands, stored in the nearshore areas and on the beaches, move into the heads of the canyon at such a rapid rate that they build a slope which exceeds their angle of repose. Under such conditions, the individual grains never come to rest, but instead move downslope as a loosely packed surficial layer of flowing grains Observation of such sand flows show that the underlying sediment, as well as the rock walls confining the flow, are eroded On occasions, the flow of sand has been sufficient to cut a previously deposited fill down to bedrock Flow continues only so long as material is added at the head of the flow and the bottom slope exceeds the angle of repose Usually, small-scale flows entering a canyon from a tributary come to rest when they encounter the main fill of the canyon. The result is the development of a small fan built out over the surface of the sedimentary fill of the main branch of the canyon head (Fig. 140) The velocity of such gravity flows is variable, ranging from the almost imperceptible creep of individual grains to as much as 11 cm/sec" (Shepard and Dill, 1966, pp. 303—304). Further details may be found in Dill (1966), who notes that the sand slowly flows down steep slopes as a series of semicontinuous progressive slumps, with velocity increasing around objects that interfere with normal flow, and that pieces of granite basement up to 20 cm long are broken away and transported by the falling sand Shepard and Dill (1966, p 301) record freshly broken boulders up to 3 m across on fans below areas of known sand flows Published photographs show a number of significant features associated with the sand flows, including polished sand-chutes that mark the passage of sand-flows down the canyon side (Dill, 1964, fig 3.6), the presence of isolated large clasts in the flowing sand (Shepard and Dill, 1966, p 107, 110), and a very characteristic linear texture on the flow surface that results from the sorting of coarser detritus into lenses and stringers parallel

to the direction of flow (Shepard and Dill, 1966, fig. 139, Dill, 1964, fig. 3).

Chamberlain (1964) calculated that "periodic sand flows move tens of thousands of cubic meters of sand per year down the La Jolla canyon axes", and showed that this amount of sand was approximately equal to the total annual littoral-drift sand budget. These figures, together with the observations quoted above, demonstrate beyond doubt that sand-flow is a major effector of sediment transport in proximal canyon environments.

Most published statements on grain-flow claim that it can only operate on slopes around 30° or greater, and this supposed limiting factor has been a major reason for the rather lukewarm reception that the process has received in the interpretative sedimentology of proximal flysch facies. For instance, Middleton (1970, p. 265) states that grain-flow "takes place only when the slope is so steep as to exceed the submarine angle of repose of the sand". However, numerous published descriptions and photographs demonstrate that locally grain-flow is a major process of submarine transport, and that it may operate on slopes as low as 3°.

As noted by Dill (1966, p. 763), Shepard and Dill (1966, p. 302, 304), Andresen and Bjerrum (1967, pp 221—222) and Carter (1975) sand-flows are intimately associated with sand slumping on all scales Whatever the initial reason for a slump in sand grain sizes, once it has occurred the sediment in the head of the slump is greatly oversteepened with respect to the normal 30° angle of repose, and it fails in its turn, flowing downslope until a new stable equilibrium is reached (Fig. 6a) By this process of *retrogressive flow sliding* "even wide horizontal areas may be involved in slides of this type. The rate of development of a flow slide may be from fifty to several thousand meters per hour" (Andresen and Bejerrum, 1967, p. 221) The Scandinavian examples discussed by Andresen and Bjerrum took place on slopes down to 8°, and de Koning (quoted in Middleton, 1969) has recorded similar retrogressive flow slides on slopes as low as 3°. As large scale slumping is now documented on slopes of only 1° (Lewis, 1971), grain-flow propogated by such slumps is obviously a feasible sedimentary process in virtually any subaqueous environment.

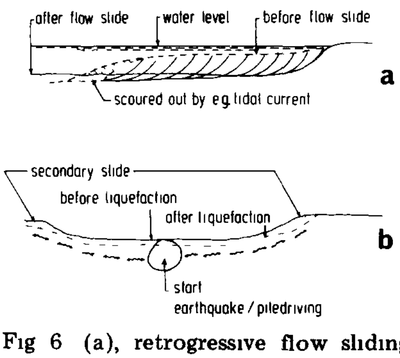

Fig 6 (a), retrogressive flow sliding, (b), spontaneous liquefaction (subsidence flow) (after Andresen and Bjerrum, 1967, see text for full details)

Slump-creep

The possibility that slow creeping processes might play a part in the transport of sand into deep water was first suggested by Lombard (1956). However, Lombard's explanation was primarily directed at the type of flysch sediments that contain good Bouma sequences, such as would now be considered typical turbidites, the idea was comprehensively criticised by Kuenen (1959), and consequently discarded. Oulianoff (1960) approached the possibility of creep from a slightly different viewpoint He noted that the Recent sea-floor is subject to constant vibration by microseismic activity, and suggested that this should cause sands to creep slowly down slope and spread out on the deep sea-floor, the mechanism was experimentally simulated by artificial vibration of a sedimentation tank Kuenen (1964) provided an effective critique of this suggestion also, but at about the same time the process of gravity creep was placed on a sound empirical basis by a team of workers at Scripps Institute of Oceanography.

A slow glacial-like gravity creep of the entire sedimentary fill in submarine canyon heads was first reported in detail by Dill (1964) An interwoven mat of kelp, sea-grass and sand (organic component up to 90%) was observed in the axis of the La Jolla canyon, proof of its "slow and downward movement is the displacement of stakes placed in tributaries at the head of the canyon, and the movement of lobstertraps, man-made debris, etc. into deeper water when incorporated in the mat during its formation at the head of the canyon" (Dill, 1964, p. 31). Erosion "is accomplished through abrasion and plucking by the sediment mat as it moves slowly down the canyon. The smooth and polished bottoms observed in sand chutes and rock tributaries after the periodic removal of their sediment covers indicate that the movement of sand gradually grinds and erodes away the rock wall" (*loc cit* , p 35). The creeping sediment is able to transport large blocks that fall onto it from the adjacent walls, or are transported by sand-flow down tributary valleys or sand-chutes (Chamberlain, 1964).

The high content of organic matter perhaps suggested that sand-creep was consequent upon gradually lessening sediment shear-strength, caused by decomposition of the organic material (Dill, 1964, Shepard and Dill, 1966). Furthermore, the process was initially only reported as occurring on slopes in excess of about 25°, and in view of these two special factors, few writers on proximal flysch have argued for a sand-creep origin for fossil sediments. However, more recently published data ameliorate these preconditions, and include the following observations

(1) Sediment creep is intimately associated with semi-continuous downslope slumping

Inferences as to mass-movement in Recent canyon fills is difficult if the fill is entirely sand Fortunately in at least some cases a thin layer of soft mud blankets the surface and acts as a sensitive indicator of movements

within the underlying sands. Shepard and Dill (1966), and more recently Shepard et al (1969), have described how such a mud-covered canyon or fan-valley floor is broken into a series of steps that range in size from small cracks to features 1 9 m in height Occasional vertical faces delimited by curved upslope scarps show that at least some of these features are a result of slumping, and their net effect is to produce a hummocky surface of gentler slope than the original unslumped fill. Such regions of slumping have been most closely studied in the head of La Jolla Canyon, but also occur at depths down to 275 m in the San Jose and Los Frailes Canyons, southern California

(2) Sediment creep may take place on extremely low slopes

Cracks and narrow ridges on the top surface of the channel fill have been described and figured from La Jolla fan-valley at a depth of 823 m (Shepard and Dill, 1966, fig. 30, Shepard et al , 1969) Though smaller scale, these features are otherwise similar to those described under (*1*) above In some cases a diagonal up-valley orientation resembles that of tension crevasses on the sides of glaciers Similar cracks in the mud cover of the fan-valley fill have been seen at depths down to 1,116 m, where the regional slope of the channel axis is less than 1°, suggesting "a slow downslope creeping motion of the entire channel fill" (Shepard et al , 1969) Polished and abraded rock walls are found at all depths in the La Jolla fan-valley channel, and are similar to those observed to be eroded by grain-creep and grain-flow in the shallower water canyon feeders

(3) Creeping sediments are closely associated with channel-axis inertia-flow conglomerates

Many examples of the association between canyon or fan-channel sands and coarse conglomerate or breccia clasts have been described from both Recent (Shepard and Dill, 1966, fig 89b) and fossil (Normark and Piper, 1969, fig. 1, Carter and Lindqvist, in press) sediments. Sometimes the coarse components occur in sediments that carry evidence of bottom traction currents, and a traction mode of emplacement is therefore possible. However, 40 cm/sec is the fastest 'normal' current velocity recorded in a study of seven Californian canyons (Shepard and Marshall, 1973), and the maximum current ever recorded in a canyon is 180 cm/sec (Inman, 1973); such currents would only be competent to entrain fine pebbles (up to about 1 cm diameter) and small cobbles (up to about 10 cm diameter) respectively In fact, many Recent canyon conglomerates commonly contain clasts in excess of these dimensions, generally in occurrences that are texturally more similar to debris-flow deposits than to tractionites. Such conglomerates have been described from 610 m in the La Jolla Canyon, at 1,370 m in outer San Jose Canyon, at 1,143 m and 2,260 m off Baja California (Shepard and Dill, 1966, p 63, 118 and fig. 144), and in the Cascadia deep-sea channel (Griggs and Kulm, 1970).

Sharp and Nobles (1953) have shown that subaerial debris-flows will travel

on slopes as low as 1° at their outer limits, and the same is likely to be true for their subaqueous equivalents Subaqueous inertia-flows may therefore be expected in sedimentary situations that extend well beyond the canyon-fan complex which spawned them.

Discussion
The rheologic phenomenon of creep is characterised by "an increasing deformation under sustained load, the rate of strain depending on the stress" (Flugge, 1967) Well-known geological examples include glacial creep, where ice "deforms plastically by the gliding, one over another of layers parallel to the basal plane" (Paterson, 1969), and soil creep, which is generally dependent upon substantial amounts of clay-sized particles that relieve outside stresses by plastic deformation rather than by failure along a major slip-zone (Zaruba and Mencl, 1969, Finn and Emery, 1972). Though the unqualified term creep was used by Shepard and Dill (1966, p 300) as encompassing the behaviour of the highly organic silt- to sand-sized sediments of the La Jolla and other submarine canyons, it seems likely that the process is only similar in effect, i e., analogous, with creep as rheologically defined Subaqueous "creep" may, however, be closely similar to processes of semi-continuous mass-slumping that have recently been described on steep subaerial slopes

Nemcok (1972) has described deep-seated creep of rock-masses that causes slope deformation to depths of 300 m The process is best seen in relatively isotropic rocks such as granite, and essentially consists of semi-continuous down-slope slumping — "the ridge is loosened along a set of shear planes that dip into the slope The rock mass is dissected by the planes into blocks that have moved downslope and rotated either backward or forward with relation to the slope angle The general movement of the loosened mass is toward the valley " Similar processes have been described by Jahn (1964), Beck (1967), and Tabor (1971)

The term *slump-creep* appropriately distinguishes between these processes and true rheological creep, and the prefixes subaerial and subaqueous slump-creep allow simple distinction to be made between the two presently known modes of occurrence, should such distinction be necessary Though the precise mechanism of slump-creep remains enigmatic, its reality and importance as a means of sediment transport is beyond dispute

Turbidity current carpets bed-load inertia-flow fluxoturbidites

Slurry-flow
The concept of a process intermediate between a watery slide and a true turbidity current initially stems from a report on laboratory work by Kuenen (1951, p 15), who observed (Kuenen, 1956, p 138) "a transitional type of movement between a turbidity flow and slumping Part of the suspension, when densities of 1 5 or higher were used, shot along the bottom over a distance of some metres in a thin wedge lagging only slightly behind the nose of the overlying turbidity current It formed an unsorted

deposit of the composition of the suspension. The high velocity suggests a low viscosity, the shape and the sharp boundary with the turbidity current argue for a non-turbulent type of flow To this uncertainty concerning the nature of the flow must be added that it is doubtful whether it occurs under natural conditions " A little later, by then convinced of the likelihood of occurrence of beds deposited by this mechanism in flysch deposits, Kuenen (1958) introduced the term "fluxoturbidite", but the first full description of supposed fluxoturbidite deposits appeared in Dzulynski et al. (1959) Unfortunately, these latter writers used the term fluxoturbidite, which had originally been conceived as descriptive of the products of a *process* (i.e , a fluxoturbidity current), as a general facies descriptor, a usage perpetuated by nearly all later writers (see comprehensive summary in Walker, 1970, p. 236) It follows that the widely quoted attributes suggested by Dzulynski et al to be typical of the fluxoturbidite facies, actually apply to beds that were deposited by a whole range of submarine mass-transport processes

For the experiments reported by Kuenen (1951), a viscous clay suspension was used Following arguments advanced previously, it is therefore likely that transport within the lagging basal wedge was by slurry-flow Similar experiments have recently been reported by Hampton (1972), whose description of the process essentially agrees with that of Kuenen, but whose elegant theoretical explanation suggests that the high concentration wedge of slurry itself generates the overlying turbulent layer by reverse shear in the head region

Grain-flow

In an attempt to explain the often mutually exclusive distribution of flute and groove casts, Hsu (1959) suggested that a high-concentration granular wedge of sediment might form at the base of a depositing turbidity current "a thin sheet of fluidized sediment mass of high viscosity is thus formed between the turbidity flow and the muddy sea bottom This mass is forced to continue its forward motion, for a short distance at least, because of the strong shearing stress being exerted on the mass by the turbidity flow above. As the Reynolds number is small for a fluid of high viscosity, the fluidized sediment mass at the bottom of a turbidity current moving at low velocity must therefore assume laminar motion" (p. 534). This idea was developed further by Dzulynski and Sanders (1962), who introduced the term "traction-carpet" for its description, and particularly by Sanders (1965). However, as Middleton has stressed (1970, pp 266—267, and quotation below), one of the most distinctive features of deposition from grain-carpets basal to a turbidity flow is the absence of movement by true traction, and the presence of a pervasive laminar shearing, thus the term traction-carpet is not particularly appropriate and will not be used in this sense here

The existence of such a flowing-grain layer at the base of a depositing turbidity current has been strikingly confirmed by Middleton (1967, 1969). In contrast with most earlier experimenters, Middleton's suspensions con-

tained no mud phase, but consisted only of solid plastic spheres mixed with water. When the concentration of the initial turbidity flow was greater than about 30% by volume, "sediment deposition began a short distance behind the head, as with low concentration flows, but subsequent events were very different Movement on the bed of the first-deposited particles did not stop almost immediately, as with low-concentration flows, but continued to take place by shear of the bed (*not* by rolling or sliding of individual particles) The bed did not appear to accumulate grain-by-grain or layer-by-layer Instead, it was first difficult to distinguish a well defined bed and when a distinct interface appeared the bed was up to 30% thicker than it was in its final form At the boundary between this expanded 'quick' bed and the flow above, waves formed, which were either almost stationary or moved downstream. The surface wave motion produced a circular shearing of particles within the upper two thirds of the thickness of the bed . . After the disappearance of the waves the bed compacted to its ultimate total thickness and the upper surface became perfectly plane The final stage in the growth of the bed was the very slow settling out of the finest particles from the 'tail' of the current" (Middleton, 1967, pp 494—495).

Nomenclature

It is likely that two separate processes of inertia-flow are involved in bed-load deposition from dense turbidity currents, and that there is probably a gradation between them. In the presence of appreciable mud, the bed-load wedge travels as a slurry, if the concentrations of dispersed solids are sufficiently high, it may even "break up into slabs or chunks that slide along separately for short distances" (Kuenen, 1951, see also Hampton, 1972) Grain-flow sensu stricto does not usually occur, though a Bagnoldian dispersive pressure produced by flow in the viscous regime may be operative, the process is appropriately described as being intermediate between slumping-sliding and turbidity flow. In the absence of mud, on the other hand, the bed-load wedge travels as a true "flowing-grain" layer, i e , Bagnoldian grain-flow in the intertial regime takes place and results in substantial intergranular dispersive pressure (Sanders, 1965, Stauffer, 1967, Middleton, 1967) As Middleton (1970) has stressed, all intermediates are possible between these two types of behaviour, and in the present state of knowledge it would be unwise to use a field-terminology that always required precise differentiation between the two processes, hence the value of the term inertia-flow (Sanders, 1965)

Walker (1967) has argued that since the term fluxoturbidite has been applied to a facies, a process and a bed, it should be dropped. However, the term was initially and clearly introduced as descriptive of the sedimentary results of a theoretical process, the general validity of which has been confirmed experimentally by Kuenen (1951), Middleton (1967) and Hampton (1972), though continued usage of the term might seem confusing, the coining of new terms appears even less desirable The course adopted here is to

retain the term in the sense in which it was originally proposed, as descriptive of the deposits of a *fluxoturbidity process*, but in the light of the discussion above, it is suggested that Kuenen's concept be interpreted widely, i e., as encompassing bed-load grain-flow as well as the slurry-flow that he described experimentally

Hence a fluxoturbidite is construed here as any bed deposited from the basal layer of a dense turbidity current in which the immediately pre-depositional transport was by inertia-flow (*sensu* Sanders, 1965) The term is then useful in a field context (cf. the similar usage in Schlager and Schlager, 1973), and conveniently solves the terminological impasse discussed by Sanders and Kuenen (in Sanders, 1965). Many, probably most, fluxoturbidites are therefore a type of proximal turbidite (as Walker, 1967, has stressed), but the other lithologies that occur interbedded in such facies, for the sum of which the term fluxoturbidite has been widely used following Dzulynski et al. (1959), are only fluxoturbidites if it can be reasonably inferred that they too were deposited by inertia-flow from the base of a fluxoturbidity current

III A SUGGESTED TERMINOLOGY FOR SUBAQUEOUS MASS-TRANSPORT PROCESSES AND PRODUCTS

As pointed out by Cooke et al. (1972), the most confusing aspect of the present nomenclature for subaqueous mass-transported sediments stems from the fact that the majority of authors fail to separate the processes of *initiation* of mass-transport from the mass-*transport* itself, or from the sedimentary *deposits* that result from emplacement by mass-transport Thus terms such as debris-flow are loosely used both in description of a process (slurry-flow of this paper), and in description of the final sedimentary deposit of that process (generally a poorly sorted muddy breccia-conglomerate) The clearest nomenclatural treatment to date is that of Dott (1963) whose terms subaqueous rockfall, slump and sliding, mass-flow and turbidity flow clearly apply to transport processes. However, a range of processes may act within the general compass of mass-flow as defined by Dott, including at least grain-flow, slurry-flow, and slump-creep and it seems essential that these processes (and probably their depositional products) be nomenclaturally differentiated. As Dott points out, a given sediment may travel by all four major types of mass transport during its transit down slope, and even where only one of the transport processes is involved, the nomenclatural situation may still be complex, e.g. a mass of sand might be mobilized by liquefaction, transported by grain-flow, and deposited by freezing

In general, it may be expected that the processes of deposition, and perhaps transport, will be able to be inferred from the preserved sediments Though the factor or factors that caused mobilisation will generally be more speculative, we nevertheless require a nomenclature that clearly distinguishes between all these different facets of mass-transport, and that allows reason-
covers both processes is therefore essential, and Sanders' term *inertia-flow*

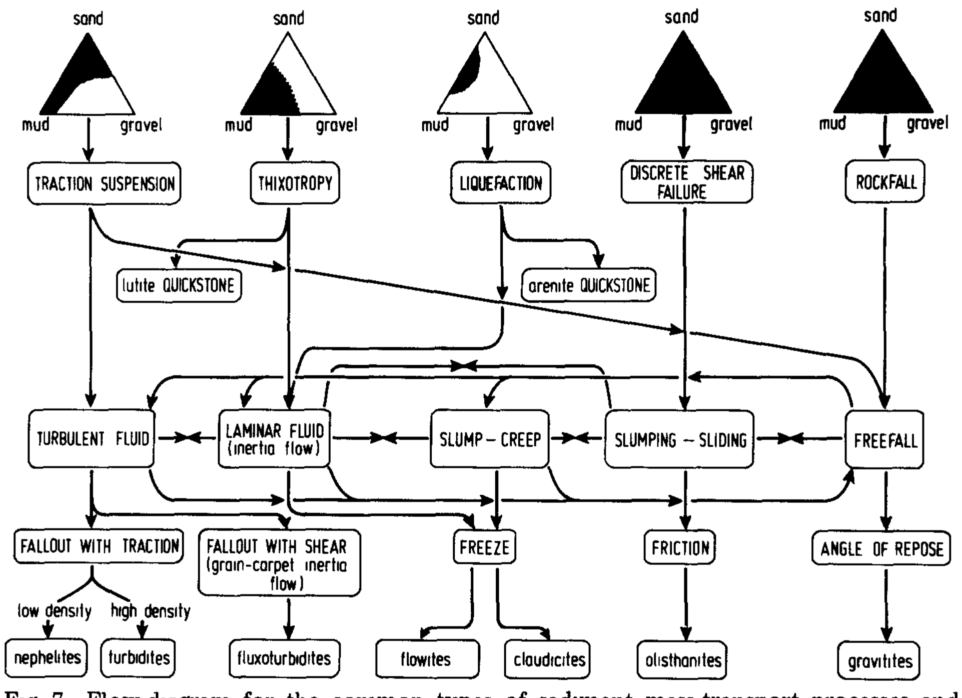

Fig 7 Flow-diagram for the common types of sediment mass-transport processes and their products The shaded areas in the triangular grain-size diagrams represent the sedimentary grain-sizes affected by the entrainment process specified beneath the triangle From the top of the figure downwards, the horizontal lines of terms correspond to sediment entrainment, transport and deposition The bottom line of terms comprises bed or facies descriptors for sediments deposited from the various types of mass-transport Identical sedimentary products may result from a variety of very different paths across this diagram, as shown by the many different flow-paths indicated by arrows

able genetic inferences to be unambiguously expressed Various flow-paths representing possible mass-transport histories are depicted in Fig 7, and the new terms that are used here in a precisely defined sense, are listed in the glossary below

SUMMARY AND CONCLUSIONS

(1) Within the spectrum of subaqueous mass-transport processes, turbidity currents have been overemphasized by comparison with laminar mass-flow mechanisms

(2) Adequate understanding of mechanisms controlling transport and deposition of laminar mass-flows is precluded by a lack of detailed experimental evidence It is therefore necessary to exercise care in arriving at a descriptive terminology for laminar mass-flow. For many field examples it is possible to infer emplacement by laminar mass-flow, but not to ascertain whether transport was strictly by grain-flow or slurry-flow A term that

was proposed for just such a purpose, if deemed unsuitable, then a new term is required

(3) The distinction between inertia-flow and turbidity flow is fundamental, and should not be glossed over because of our ignorance of the precise physical mechanisms operative in inertia-flow. Many fossil proximal flysch facies contain beds that have probably been deposited by inertia-flow rather than turbidity currents The development of field criteria by which various inertia-flow deposits can be recognised as distinct from each other, and from turbidites, is a most pressing need

(4) Though the slopes that generate many inertia-flows are moderately steep, flow maintenance requires only gentle slopes, probably less than 1° Further, evidence is rapidly accumulating that even the generation of inertia-flows may not require slopes of more than a few degrees Decisions regarding the emplacement of specific beds should therefore be based on outcrop data, and not restricted by empirical calculations of the slope required before various hypothetical flow mechanisms can operate

(5) Slump-creep operates on Recent slopes of less than 1° Recent occurrences of slump-creep are sufficiently widespread for its apparent absence from fossil sediments to be treated with suspicion Fossil canyon and fan-valley sediments are being described in increasing numbers, and some of these occurrences should show evidence for emplacement by synsedimentary slump-creep. The term *claudicite* is proposed for a bed or facies emplaced by slump-creep.

(6) The terms *grain-flow*, *debris-flow* and *fluxoturbidite* have been used in a wide variety of ways by different authors The continued meaningfulness of these and other similar terms depends upon their careful and practical definition. Provisional definitions of terms covering a variety of mass-transport phenomena are listed in the appendix The meanings adopted are generally those with historical precedence

(7) A preliminary classification covering subaqueous mass-transport phenomena is outlined in Fig. 7 The skeletal nomenclature used will undoubtedly need future refinement, and some of the terms used may not find ready acceptance It is nonetheless important that future classifications maintain clear terminological distinctions between the conceptually discrete processes of sediment *entrainment*, *transport* and *deposition*

GLOSSARY

Claudicite (from claudicant, lame or halting). a bed, or facies, inferred to have been subaqueously transported by slump-creep, because of the general restriction of this transport mechanism to submarine channels, the claudicite facies usually contains intimate admixtures of sediment previously transported by free-fall and inertia-flow.

Creep (rheologic) "an increasing deformation under sustained load, the rate of strain depending on the stress" (Flugge, 1967)

Debris flow: a slurry-flow transport mechanism in which appreciable numbers of suspended clasts are present in the slurry; the term is also often used to describe the deposits of such a flow

Flowite a bed, or facies, inferred to have been transported dominantly by inertia-flow.

Fluxoturbidite a bed, or facies, deposited from the basal layer of a fluxoturbidity current, i e , a turbidity current in which the immediately predepositional transport of the basal layer was by inertia-flow

Grain-flow a transport mechanism in granular sediments in which shear is general, every grain moving relative to its neighbours, transfer of momentum is by intergranular impacts that also generate a dispersive pressure, flow is essentially laminar (= grain-flow in the inertial region of Bagnold, 1956)

Gravel-flow· grain-flow in which the granular component comprises dominantly clasts in the gravel size range

Gravitite a bed, or facies, inferred to have been emplaced dominantly by gravitational freefall

Hydroplastic "having the property of plasticity due to the presence of adsorbed water films and interstitial liquids" (AGI glossary)

Inertia-flow "transportation of sediment in which grains move above the bottom but are not supported by upward components of the turbulent movements within the fluid the grains move differentially within the fluid and owing to their inertia, follow linear paths ." (Sanders, 1965, p. 329), as so defined, the term encompasses both grain-flow and slurry-flow (q v)

Nephelite a bed, or facies, inferred to have been transported in a turbulent fluid of very low excess density, *a bottom turbid layer*, such turbid layers "differ from the usual concept of turbidity currents in that they are not necessarily elongate in the direction of net movement, they have an oscillatory trajectory, and downslope gravity flow may be insufficient to sustain turbidity" (Moore, 1970)

Olisthanite a "bed", or facies, inferred to have been emplaced by synsedimentary sliding or slumping without appreciable distortion of the body of the moving sediment mass. (N B , this usage differs from that of De Raaf (1968) who used olisthanite for specifically small scale phenomena (contrast olisthostrome) that encompassed the entire range of subaqueous massflow and slumping, as intended here, the term carries no restrictions as to scale, and specifically excludes inertia-flow or hydroplastic phenomena)

Quickstone a bed of generally granular sediment that deforms plastically some time after initial deposition, deformation takes place *in situ*, generally due to hydroplasticity (Elliston, 1963).

Sand-flow inertia-flow in which the granular component comprises dominantly sand-sized material

Slump-creep. a transport mechanism involving the slow glacial-like creep of a previously deposited mass of sediment, such as the fill of a submarine canyon, such creep is intimately associated with slumping on all scales, and may occur subaerially (Nemcock, 1972) or subaqueously (Shepard and Dill, 1966)

Slurry-flow a transport mechanism of inertia-flow type involving a suspension of clay grade fines in water; shear is general, and if dispersed granular material is present, a dispersive pressure generated by ordered shear velocity changes as grains approach one another is added to the dilatant behaviour of the fine-grained suspension (= grain-flow in the viscous region of Bagnold, 1956)
Turbidite a bed, or facies, inferred to have been emplaced from a turbidity current
Turbidity current a gravity current in which the excess density causing flow is due to autosuspended sediment (Bagnold, 1962)

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The classification and terminology of mass-transported sediments that is developed in this paper grew out of field work on Cainozoic submarine mass-flows from southern New Zealand. During the writing up of the field-work, it became apparent that the nomenclature of mass-transport found in the literature is often confused or ambiguous, and that it all too rarely meets the requirements of the geologist in the field Therefore, and though it draws heavily on relevant laboratory and theoretical work, this paper basically represents an attempt to meet the nomenclatural needs of the field-worker. I am grateful to the many colleagues who have helped me during this work, but particularly to Mr. J.K Lindqvist for his company in the field, and to Drs. D G. Bishop, C A. Landis and R.J Norris for their critical readings of an early draft manuscript The financial support of the New Zealand University Research Grants Committee is gratefully acknowledged

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