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Stream-driven, high-density gravelly traction carpets: possible deposits in the Trabeg Conglomerate Formation, SW Ireland and some theoretical considerations of their origin

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ABSTRACT

Within high-density flood flows a prominent mechanism of gravel transport and deposition is by stream-driven, high-density traction carpet (with a rheology similar to grain flow). These gravel carpets are envisaged to form the basal portion of a bipartite high-density flood flow, decoupled from an overlying sand- and silt-laden turbulent flow. Several examples already documented in the literature are reviewed and an additional case from the Lower Old Red Sandstone of southwest Ireland is presented. Two mechanisms of traction carpet initiation are discussed: by rapid entrainment of gravel into suspension on rising stage, followed by settling into the gravel traction carpet at peak and falling stage; and by overconcentration of a 'normal', low-density bedload. Gravel entrainment, suspension and traction carpet development are significantly easier if the flood water already carries a high concentration of sand and silt in suspension. Theoretical consideration further shows that gravelly traction carpets can be maintained in channels of relatively low gradient by the shear stress exerted by the high-density, sand-bearing turbulent flood flow above. This tangential shear stress is converted to dispersive pressure, which aids buoyancy and quasi-static grain-to-grain contacts in the support of the clasts within the gravel carpet. The carpet is thought to have a quasi-plastic rheology but behave much like a viscous fluid at high shear rates. Stream-driven gravelly traction carpets are expected to produce sheet-like units of clast- to matrix-supported conglomerate, characterized by a parallel or an *a*(p)*a*(i) clast fabric. These units may be ungraded, normally or inversely graded, depending on the rate of shear, the viscosity of the flow and the celerity of deposition.

INTRODUCTION

Interpretations of conglomeratic alluvial sequences have commonly involved comparisons with the products of modern gravel-bed rivers (e.g. Smith, 1974; Boothroyd & Ashley, 1975; Hein & Walker, 1977). In particular, sheet-like units of massive, clast-supported conglomerates (Casshyap & Tewari, 1982; Mathisen & Vondra, 1983; Rust, 1984; Kraus, 1984; Middleton & Trujillo, 1984; Morrison & Hein, 1987) have often been compared to Facies Gm and the Scott facies model of Miall (1978). Whilst some of these ancient sediments bear close resemblance to their supposed modern counterparts, the simple analogies drawn do not fully explain the transport and depositional mechanisms involved in the emplacement of the conglomerates. Part of the inadequacy of these uniformitarianistic comparisons stems from the difficulty of studying the transport of gravel in modern rivers, because this tends to occur during the highest flood stages making investigation problematic. This is compounded by the low frequency of recurrence of high magnitude floods, which may be separated by hundreds of years (Baker, 1977).

The sedimentological study of modern debris-flow processes and products is also hindered by similar problems. Benefits have been gained from theoretical approaches and careful analyses of ancient deposits

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(e.g. Walker, 1975; Middleton & Hampton, 1976; Lowe, 1979; 1982; Allen, 1981; Hein, 1982; Nemec & Steel, 1984; Porębski, 1984; Postma, Nemec & Kleinspehn, 1988). Following the earlier concept of Dżułyński & Sanders (1962), Lowe (1982) has deduced, for example, that some deep-sea gravel units may be the product of traction carpets (or current-driven and density-modified grain flows, *sensu* Lowe, 1976) developed at the base of high-density turbidity currents. Thin gravelly traction carpets have been produced in the laboratory (Postma *et al.*, 1988). They are driven by the shear stress exerted by the less concentrated, turbulent, upper portion of the turbidity current (Lowe, 1982; Hein, 1982; Postma *et al.*, 1988). The carpet represents a quasi-plastic substance (with a yield strength), though at high shear rates, behaves much like a normal (Newtonian) fluid (Middleton, 1967; Postma *et al.*, 1988).

The occurrence in alluvial settings of flows with a rheology transitional between plastic and fluid has also been inferred by some authors (e.g. Nemec & Muszyński, 1982; Nemec & Steel, 1984; Smith, 1986). The deposits of such 'hyperconcentrated' flows would be expected to share many features in common with the products of debris flows (Allen, 1981; Nemec & Muszyński, 1982; Ballance, 1984; Nemec & Steel, 1984; Pierson & Scott, 1985; Smith, 1986; Pierson & Costa, 1987). These high-density stream floods are likely to be bipartite, containing both plastic and fluid portions. This type of flow is further assessed in this paper. It is contended that current-driven, density-modified 'grain flows' (traction carpets) can be an important process of transport and deposition in the upper reaches of gravel-bed rivers which have relatively steep gradients and/or respond to high magnitude floods. A new example of the inferred deposits of such gravelly traction carpets is first presented. Previous examples from the literature of both the process and the products of deep-sea and alluvial gravelly traction carpets are then reviewed. Finally the physical conditions necessary for the development of such carpets are assessed.

CLAST-SUPPORTED CONGLOMERATE SHEETS IN THE TRABEG CONGLOMERATE FORMATION OF SW IRELAND

Description

The Trabeg Conglomerate Formation of the Dingle Group (Lower Old Red Sandstone) crops out in the south of the Dingle Peninsula (Fig. 1) and is likely to be of Early Devonian age (Horne, 1974; Todd, Boyd & Dodd, 1989; Todd, 1989). The formation is composed mainly of conglomerates, with subordinate sandstones and siltstones, and is interpreted to be the deposits of a stream-dominated alluvial fan (Todd *et al.*, 1989; Todd, 1989).

The formation is characterized by stacked sheets of massive (unstratified) clast-supported conglomerates of pebble to boulder grade (Fig. 2). The sheet-like units are a few decimetres to over 3 m thick. Conglomerate units thinner than 0·2 m are usually of pebble grade, moderately sorted, normally graded, with well developed *a*(t)*b*(i) imbrication. These thinner conglomerates are intimately interbedded with lenticular sandstone units (Fig. 2).

Thicker (>0·4 m thick) conglomerate sheets are usually pebble to cobble grade, or in some cases boulder grade (Fig. 2). Basal surfaces of the beds are sharp and irregular, with a maximum observed relief of up to 0·5 m (Fig. 2). The conglomerates are poorly to moderately sorted, have a loose to moderately tight packing, and comprise material from very coarse sand to boulder grade. Matrix, arbitrarily defined as material up to small pebble grade, fills the interstices between clasts and in some units is sufficiently abundant as to support many of the framework clasts. The framework clasts are composed of wacke, arenite, phyllite, limestone, granite and vein quartz, and are mostly moderately well rounded (e.g. roundness averages 0·73, on the Krumbein scale, for the wacke clasts).

There is little or no internal stratification in the thicker conglomerates. Individual units are typically ungraded (82%), commonly inversely graded (17%) or infrequently normally graded (1%) (Fig. 2). A pervasive planar fabric, formed by the alignment of the *ab* planes of the clasts parallel to bedding, is well developed in all but the coarsest conglomerate beds. Imbrication also occurs in isolated clusters of a few inclined clasts (cf. Brayshaw, 1984). Where beds are exposed in vertical cross-section it can often be seen that imbrication tends to occur in the basal or topmost parts of the units and that often significantly different palaeocurrent directions are recorded from the top and bottom of single units. Where lower bedding planes or internal parting planes are exposed it can be appreciated that the *a* axes of the clasts tend to be parallel to the palaeoflow direction inferred from the imbrication (Fig. 3).

There is a positive curvilinear correlation between maximum particle size (MPS) and bed thickness

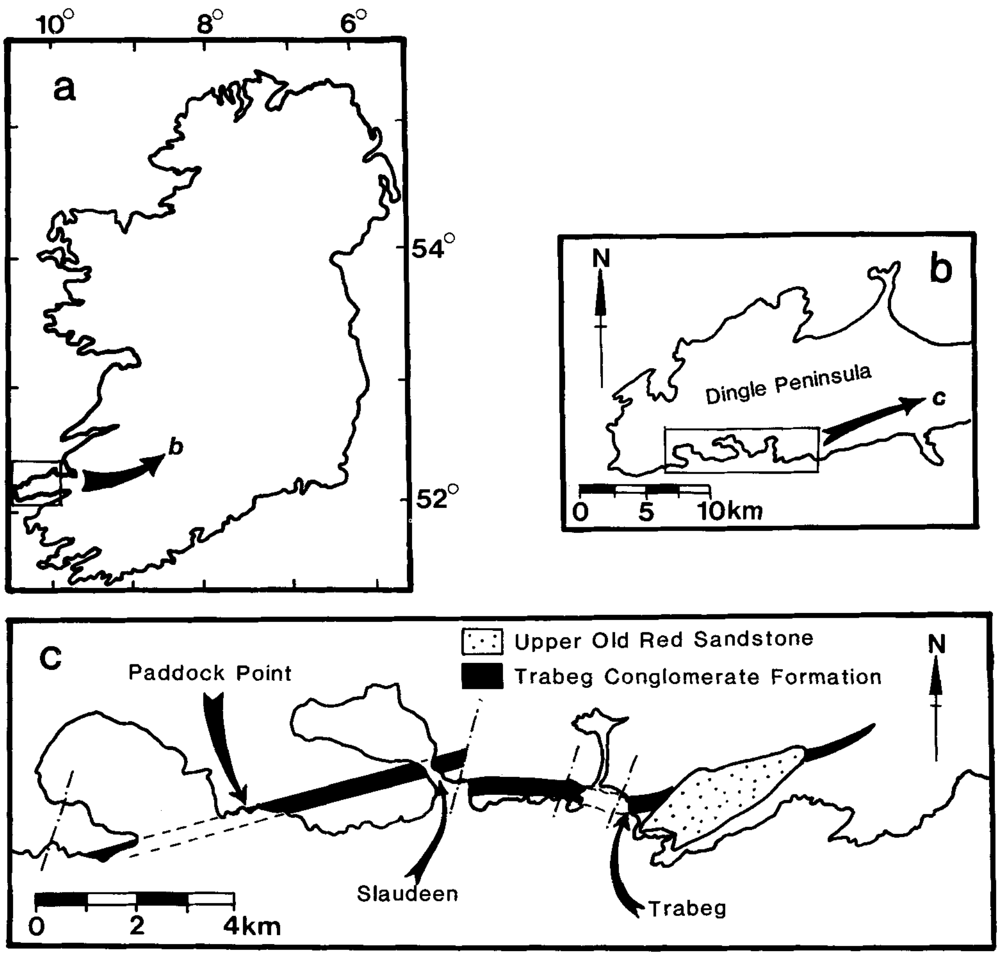


Fig. 1. Location and outcrop distribution of the Trabeg Conglomerate Formation. (a) Location of the Dingle Peninsula in southwest Ireland. (b) Map of the Dingle Peninsula showing location of the geological map of the Trabeg Conglomerate Formation depicted in (c).

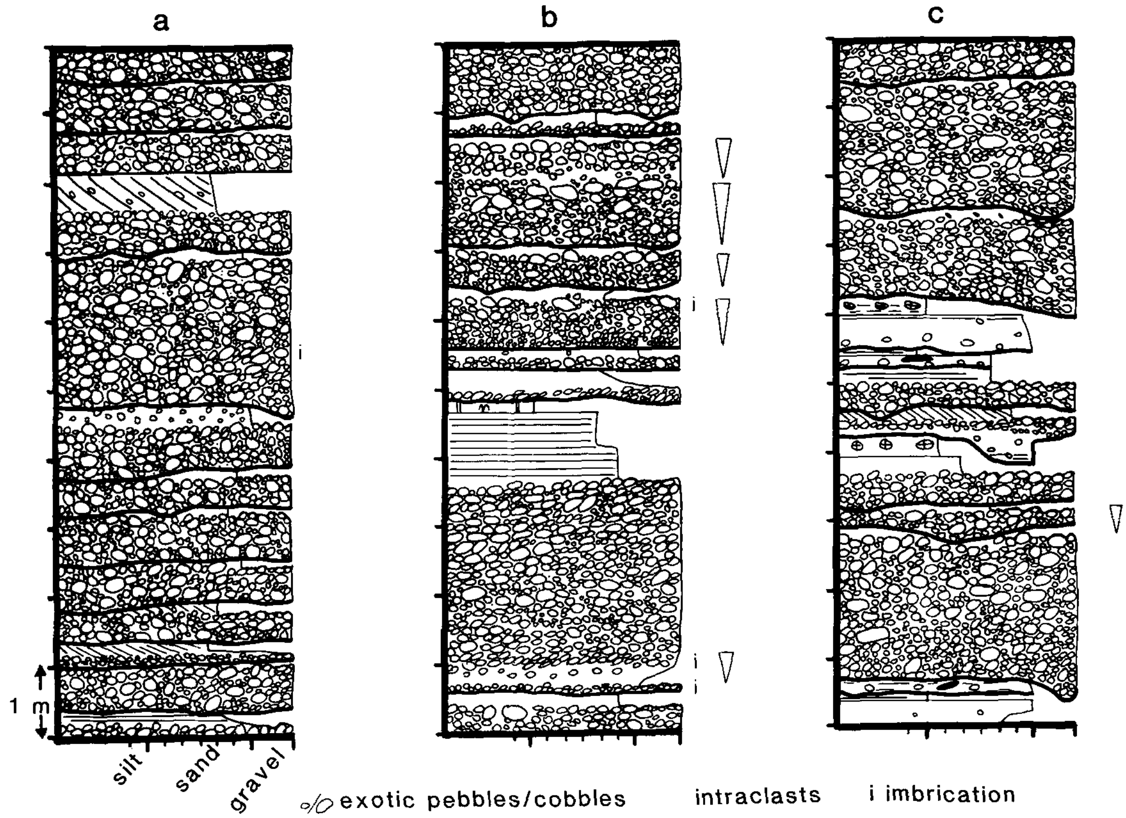
(BTh) (Fig. 4). There is also a correlation between MPS and erosive relief measured at the base of the bed within the lateral limits of the exposure (Fig. 5).

The conglomerates are most frequently capped by sandstones (Fig. 2) which are medium to very coarse grained and form units less than 0·5 m thick. The sandstone units are often lenticular, cut out by the succeeding conglomerate unit (Fig. 2). The sandstones have sharp bases that drape the irregular topography of the clasts projecting from the top of the underlying conglomerate unit. Internally, the sandstones are usually massive or parallel-laminated or less frequently planar cross-stratified. The sandstones locally contain outsize exotic clasts and siltstone intraclasts. Primary current lineation was observed in three instances. The palaeoflow direction recorded from these is approximately parallel to the palaeoflow direction inferred from the clast imbrication in the conglomerates.

Muddy siltstones are also interbedded with the conglomerates. These form generally thin units which are parallel laminated and contain burrows, desiccation cracks and small calcrete nodules (Fig. 2).

Interpretation

The deposits are of fluvial origin and represent sedimentation on a stream-dominated, 'flashy' alluvial fan (Todd, 1989). The thinner conglomerates de-



exotic pebbles/cobbles intraclasts i imbrication

deformative bioturbation calcrete upward coarsening

Fig. 2. Representative facies logs through the clast-supported conglomerate association of the Trabeg Conglomerate Formation.

scribed above are clearly the products of deposition from 'normal', grain-by-grain, tractional bedload. The conglomerates are sorted and bimodal indicating working of the sediment into different grain-size fractions during transport. The sandstones that commonly succeed the thinner conglomerates are interpreted to be the products of upper flow-regime plane-bed conditions (parallel lamination), small transverse or side bars (tabular cross-stratification), and in-channel dunes (trough cross-stratification). Together, the thinner conglomerates and the associated sandstones represent the channel deposits of low-sinuosity, possibly braided, sand-bed streams. Muddy siltstones with calcrete are interpreted to represent overbank deposits, or alternatively, muddy plugs to ephemeral channels.

The thicker sheets of clast-supported conglomerates display features that are consistent with deposition from stream bedload, and compare well to Facies Gm of Miall (1978). However, it is considered that these thicker units were largely deposited *en masse* rather than grain-by-grain from traction. This accounts for the lack of sorting and internal stratification. The units have a polymodal grain size distribution suggesting that sand and gravel were transported and deposited together. The pervasive bedding-parallel clast fabric in most beds suggests that the gravel layer experienced full laminar shear prior to freezing (Fisher, 1971; see Enos, 1977). The cluster bedforms with an *a*(p)*a*(i) clast fabric indicates that deposition was from a concentrated grain dispersion in which grain-inertia effects were prominent (Rees, 1968; Hein, 1982; Postma *et al.*, 1988). The relationship between MPS and BTh indicates that flow competence was proportional to flow thickness; another feature consistent with a mass flow origin (Bluck, 1967;

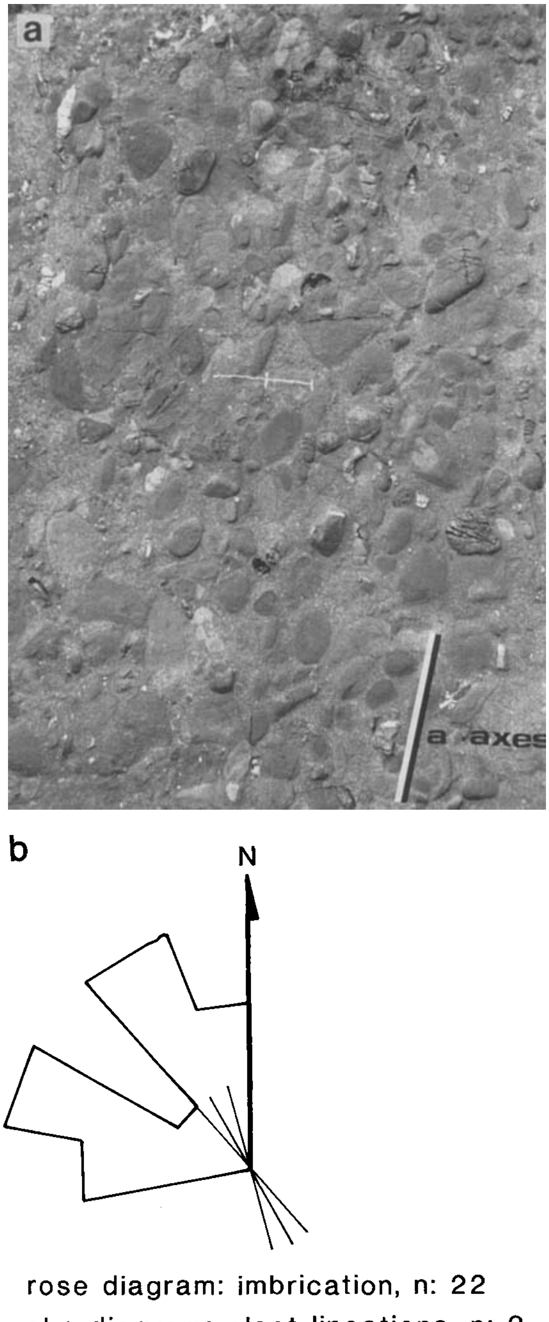


Fig. 3. Palaeocurrent data for the conglomerates at Paddock Point (Fig. 1). (a) Photograph of the base of a conglomerate unit illustrating the sedimentary lineation of the *a* axes of clasts in a direction which is parallel to the palaeoflow inferred from imbrication seen in profile from the same conglomerates. (b) Rose and spoke diagram of imbrication and clast lineation data collected from Paddock Point.

Nemec & Steel, 1984; see also Steel & Thompson, 1983). The curvilinear form of the relationship is possibly indicative of the action of dispersive pressure (Bagnold, 1954) in the support of the clasts in the flow (W. Nemec, per. commun.).

The conglomerates commonly form the thicker, lower portions of fining-upward bipartite units (Fig. 2), composed of conglomerates with erosive bases depicting most powerful flow and sandstone cappings representing waning flow. The conglomerates thus represent deposition from stream bedload rather than self-sustained mass flows (Fig. 6). Accordingly, it is inferred that the gravel moved as high-density dispersions along the bottom of channels during high magnitude floods. These high-density bedload carpets are thought to be somewhat analogous to the traction carpets driven by high-density turbidity currents (Lowe, 1982; Postma *et al.*, 1988). The principal driving mechanisms for the carpets is thought to have been the tangential shear stress exerted by the overflowing turbulent portion of the sediment-laden flood flow. This shear stress would be transmitted downwards and converted to dispersive pressure by the collisions (inertia regime) and near-collisions (if in the viscous regime) of the clasts within the bedload carpets. Dense interstitial matrix of watery sand would provide additional enhanced buoyant lift to the larger clasts. Hence the conglomerates are thought to have been emplaced by high-density traction carpets of the grain-flow type.

The close spatial relationship between the thin conglomerates, interpreted to have been deposited from 'normal' (low-density) bedload and the thicker conglomerates, interpreted to have been deposited *en masse* from high-density traction carpets, suggests that the two processes worked together in the same stream flood but were controlled by slope and depth of flow.

The stream-driven carpets had a modal thickness of 0·5 m (Figs 2 & 4). The competence of the bedload carpets (as measured by MPS of the deposits) appears to have been related to their thicknesses (Fig. 4). This is probably due to the dependence of dispersive pressure on the thickness of the flow (Nemec & Steel, 1984). Moreover there is a relationship between the competence and the amount of erosive relief of the channel (Fig. 5). This is thought to indicate that the most powerful, most erosive flows were capable of developing and driving the thickest bedload carpets.

Distribution inverse grading in the deposits of cohesionless debris flows is probably produced by the effect of dispersive pressure (e.g. Nemec & Steel, 1984). The migration of a clast in a shearing debris

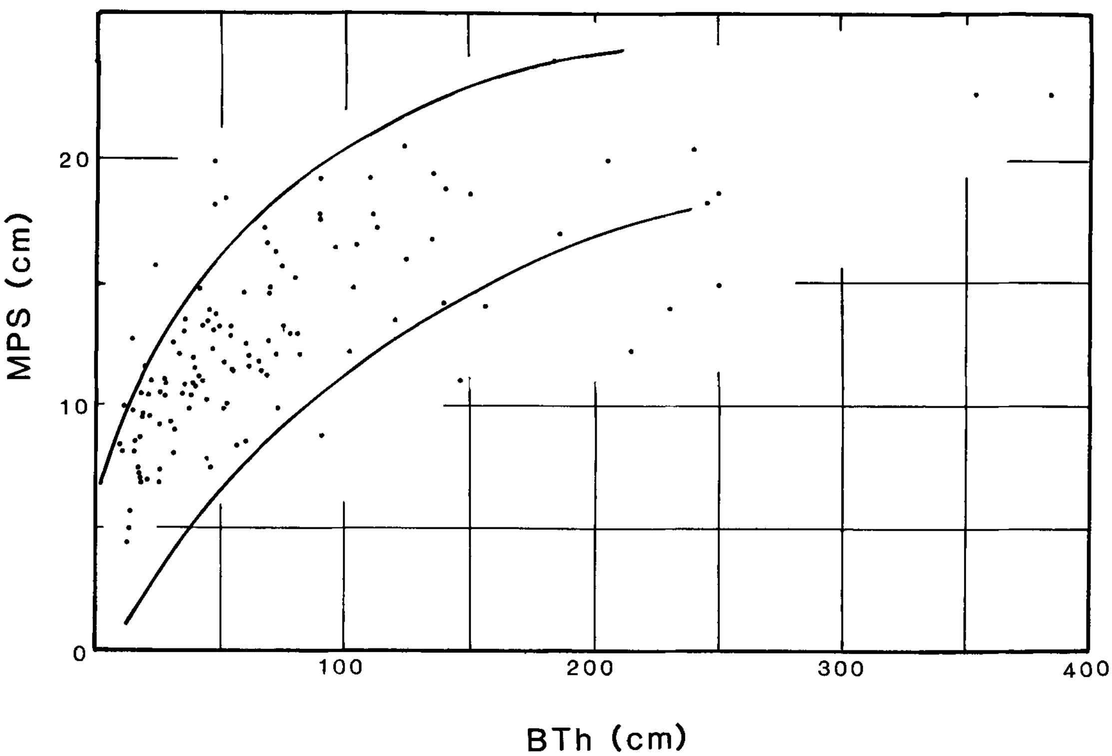


Fig. 4. Maximum particle size (MPS) *versus* bed thickness (BTh) for the Trabeg conglomerates.

flow is controlled by the apparent viscosity of the flow. Similarly, the apparent viscosity of the traction carpets that are thought to have produced the thicker Trabeg conglomerates may have varied to produce ungraded or ungraded beds. The inversely graded beds are thought to have been produced by traction carpets in which the apparent viscosity was sufficiently low and the shear-rates sufficiently high to allow the upward migration of larger clasts.

Deposition occurred by frictional freezing of the gravel traction carpets during waning of the stream flood. Sand was carried in suspension by the turbulent part of the floods. Transport of this sand probably continued after the freezing of the gravel carpets. On dissipation of the floods, the sand was deposited on top of the gravel sheets (Fig. 5). These sandstone caps were either deposited directly from suspension (producing massive sandstones which sometimes contain normal grading), or first experienced traction in upper flow regime (producing parallel lamination) or lower flow regime (producing planar cross-stratification). After the floods, silts were deposited from suspension from slack-water ponds left in the abandoned channels. This produced the siltstones in which the evidence of bioturbation, desiccation and particularly pedogenesis indicates that significant periods of time (perhaps hundreds or thousands of years) separated individual flood events.

PREVIOUS STUDIES OF CURRENT-DRIVEN GRAVELLY GRAIN FLOWS

Subaqueous flows in deep marine and lacustrine settings

Dżułyński & Sanders (1962) postulated that a highly concentrated, non-turbulent traction carpet can develop at the base of a turbidity current. The carpet is driven by the shear stress exerted by the weight of the carpet and, additionally, by the shear stress exerted by the superjacent, faster-moving, turbulent flow. The idea was elaborated by Middleton (1970), Moss (1972) and Lowe (1976). Following Aalto (1976), Lowe (1982)

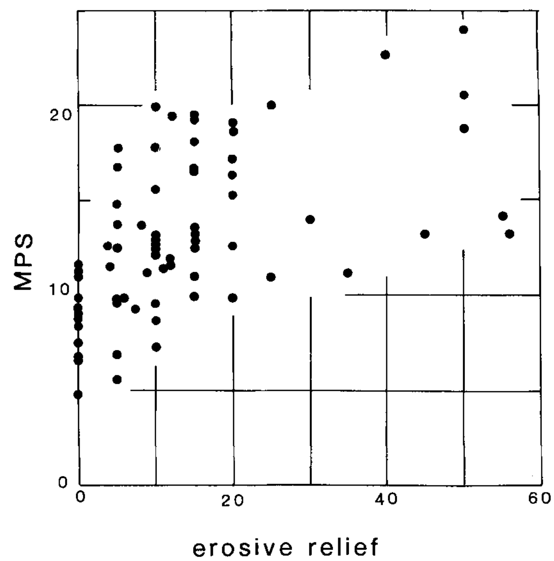


Fig. 5. Maximum particle size (MPS) *versus* erosive relief in the same unit for the Trabeg conglomerates.

described theoretically the development of a traction carpet of gravel at the base of a coarse-grained turbidity current. Gravel, initially suspended by turbulence, settles out into a concentrated basal layer in the flow. The settling of the clasts is hindered by mutual collisions and deflections, but with time the gravel decouples into a separate 'carpet' with a different rheology than the overlying turbidity current (Middleton, 1967; Postma *et al.*, 1988). The gravel carpet continues to move at the base of the turbidity current under the strong influence of the shear stress exerted by the overlying, fully turbulent part of the flow. Clasts within this basal 'traction carpet' are supported by a combination of dispersive pressure resulting from clast collisions (Bagnold, 1954; Lowe, 1982; Postma *et al.*, 1988), hindered settling (Lowe, 1982; Postma *et al.*, 1988) and buoyancy due to the relatively high density of the interstitial matrix (Hampton, 1979; Postma *et al.*, 1988). The resulting deposit is a clast-supported conglomerate which will characteristically show poor to moderate sorting, a bedding-parallel or imbricated clast fabric with *a*-axes of the clasts parallel to flow, and inverse or inverse-normal grading (Lowe, 1982; Hein, 1982; Nemec *et al.*, 1984). The inverse grading appears to be due to either the upward migration of larger clasts under the influence of the dispersive pressure (Bagnold, 1954; Lowe, 1976) or due to the emplacement of large clasts at the top of the traction carpet (Postma *et al.*, 1988). Hein (1982) argued that the thickness of the traction carpet, and consequently the thickness of the resulting gravel unit, would largely be a function of the depositional slope and the thickness and density of the overlying less concentrated, turbulent portion of the turbidity current itself.

Subaerial flows in alluvial settings

Deposits of sediment gravity flows have frequently been described from modern and ancient, gravel-bearing alluvial successions (e.g. Blackwelder, 1928; Bluck, 1964, 1967; Hooke, 1967; Larsen & Steel, 1978; Allen, 1981; Gloppen & Steel, 1981; Pierson, 1981; Nemec & Steel, 1984; Nemec *et al.*, 1984; Shultz, 1984; Wells, 1984; Blair, 1987; Morrison & Hein, 1987). The interpretations presented in these studies have generally considered the movement of sediment *en masse* under the direct drive of gravity. Fewer accounts involve the interpretation of gravelly units as the products of flows transitional between plastic and fluidal flows, or of bipartite flows which involve both types of rheological behaviour (Nemec & Muszyński, 1982; Ballance, 1984; Schultz, 1984; Pierson & Scott, 1985; Smith, 1986; Pierson & Costa, 1987).

One of the first descriptions of the products of stream-driven gravelly traction carpets was by Scott & Gravlee (1968) who concluded that gravel berms formed by a flood surge on the Rubicon River, California were the products of not normal grain-by-grain bedload but 'thick subaqueous debris flows'. One of the flows froze within the river to preserve a boulder front over 2 m high—a feature that indicates the competency of the flood surge necessary to move the mass flow was clearly much less than that required to move the component particles individually. The gravel berms produced by these flows are often inversely graded which indicated to Scott & Gravlee (1968) that dispersive pressure was prominent in the flows as a clast support mechanism.

Another example of a bipartite flow on a modern high gradient alluvial fan was presented by Mears (1979) who described the movement of a boulder grain flow at the base of a fluidal flood surge. One of these flows, which moved on slopes of about 5°, continued to move under its own momentum after dissipation of the flood water into the substrate.

Foley *et al.* (1978) concluded that torrential flash floods deeper than about 3 m in steep ephemeral channels transport much sediment in macroturbulent

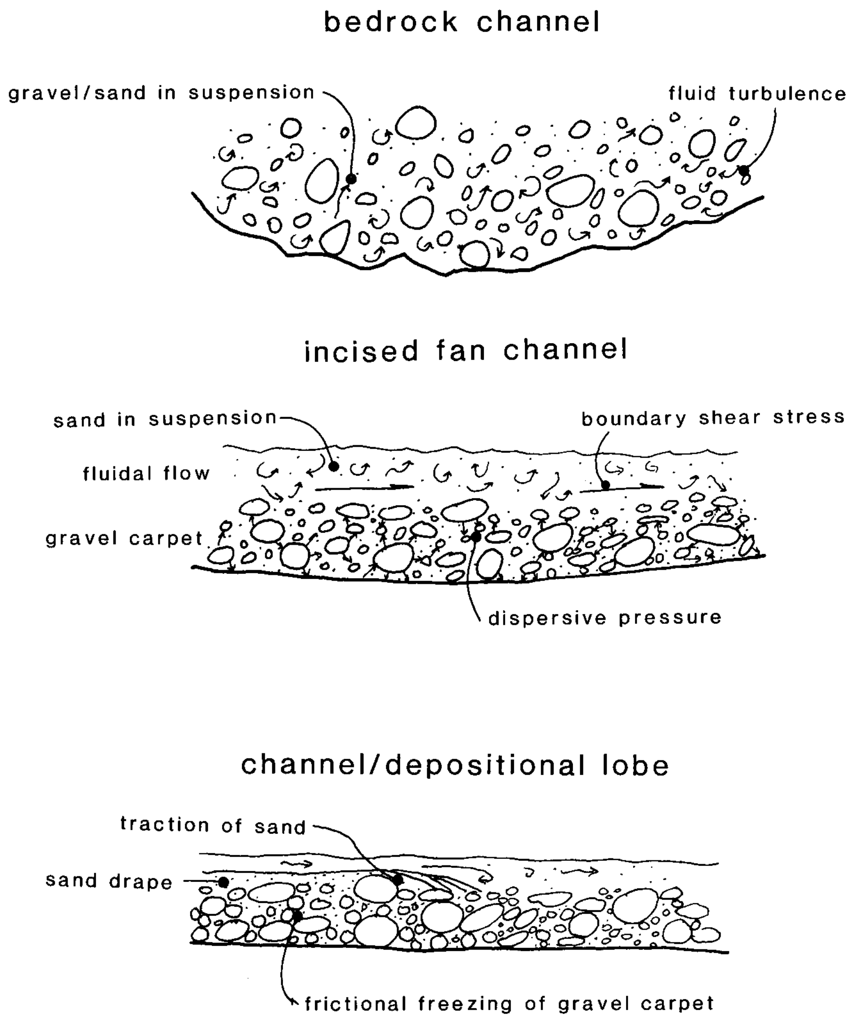


Fig. 6. Depositional model for the clast-supported conglomerates of the Trabeg Conglomerate Formation. Gravel is transported in suspension by deep macroturbulent flows within the confined reaches of the bedrock channel in the hinterland. On emergence of the channel onto the Trabeg alluvial fan the flow widens and becomes more shallow and concentrated. Gravel settles and decouples into a basal traction carpet that is propelled by the force applied by the superjacent fluidal portion of the flood which still bears sand in turbulent suspension. This shear stress is converted into dispersive pressure which supports the clasts in the flow. On flow dissipation the traction carpet freezes and is draped by the sand initially carried in suspension.

suspension or by debris underflows. They suggested that this process may also be active in shallower streams of lower discharge but are probably masked by reworking.

Allen (1981) described some thick inverse and inverse-normal graded conglomerate beds from the Devonian of Shetland. His example bears close comparison to the thick Trabeg conglomerates documented above. Whilst he noted that these deposits shared many aspects of the deposits of debris flows, he interpreted the conglomerates as the products of deposition from highly-concentrated stream floods. However, he chose to explain the variable type of grading in terms of stream discharge, rather than in terms of the dispersive-pressure effect as is considered here for the Trabeg conglomerates example.

Nemec & Muszyński (1982) and Ballance (1984) attributed sheets of clast-supported, massive conglomerates to hyperconcentrated sheet floods (cf. Beverage & Culbertson, 1964); both examples come from tectonically-active, relatively steep, alluvial fans. The sheet-like units of clast-supported conglomerate described by Nemec & Muszyński (1982) are characteristically graded but unstratified and show an *a*(i)*a*(p) clast fabric; they generally form the basal portion of an upward fining unit formed by a single flood event (Nemec & Muszyński, 1982). Nemec & Muszyński (1982) interpreted these gravelly sheets to be the result of sheet floods with a rheology intermediate between a Newtonian fluid and a Bingham plastic.

Ballance (1984) interpreted some clast-supported massive conglomerates as the product of density-modified (*sensu* Lowe, 1976) grain flows which occurred by concentration of turbulent watery flows in response to dissipation of water into the porous substrate. His interpreted example bears close resemblance to the Trabeg conglomerate sheets documented in this paper, although Ballance's scenario implies that the grain flows were self-sustained, driven solely by the shear stress derived from the down-slope component of their weight. It is contended in this paper that such gravelly grain flows may be maintained at the base of a stream channel largely by the tangential shear stress exerted by the overlying, less concentrated, faster-moving flood water.

More recently, Taconi & Billi (1987) have suggested that gravel bedload can move as a traction carpet during torrential floods. They were convinced that in one flood on the Virginio River, the bedload 'moved as a traction carpet' (Taconi & Billi, 1987).

'Hyperconcentrated' flows (*sensu* Beverage & Culbertson, 1964) may also occur in glacial settings (e.g. Lord & Kehew, 1987). Saunderson (1977) interpreted some poorly sorted gravels in an esker to be the product of a sliding bed driven by the shear stress exerted by a high-energy, turbulent water flow within a confined tunnel. The bed was thought to have moved *en masse* as a fluid/sediment mixture with some of the clasts supported by dispersive pressure. Lord & Kehew (1987) argued that the competence of glacial outbursts was significantly increased by the presence of concentrated fines within the flood water.

A somewhat unexpected example of possible current-driven gravelly grain flows comes from the Kicking Horse River. Hein & Walker (1977) describe how the longitudinal bars in the upper reaches of this river nucleate on low relief gravel layers termed 'diffuse gravel sheets', which are emplaced during peak flood conditions. These gravel sheets, which are a few clasts thick (Hein & Walker, 1977), moved like '... a carpet of ball-bearings along the (river) bed ... (F. J. Hein pers. commun., 1987). The flows were competent enough to support and transport a person standing on them (F. J. Hein, pers. commun., 1987) and it appears possible that these diffuse gravel sheets were moving by inertial grain flow with the clasts supported by dispersive pressure and enhanced buoyancy.

Possibly similar to the diffuse gravel sheets of the Kicking Horse River are the 'coarse particle waves' reported by Custer *et al.* (1987), the gravel 'bedload pulses' recorded by Reid & Frostick (1987) and the 'bedload sheets' described by Whiting *et al.* (1988). In these cases, gravel bedload was observed to move in waves or pulses. It appears probable that the clasts within these pulses were sufficiently concentrated to be influenced by collision-related dispersive pressure effects (Bagnold, 1954; 1956; 1973), and possible that the pulses could be considered as stream-driven traction carpets. However, these forms of low-density bedload conform to the definition of 'bedload' according to Bagnold (1954; 1966), who considered that some momentum transfer by grain interaction in 'normal bedload' was expected (Leeder, 1979). It is suggested that it is more appropriate to refer to such turbulent, low-density bedload layers as simply 'bedload', and reserve 'traction carpet' to thicker, high-density bedload sheets in which turbulence has been largely damped and grain interaction is the dominant means of momentum transfer. In fluvial channels, the flows developing such carpets could then be termed 'high-density stream floods'.

MECHANICAL ASSESSMENT OF STREAM-DRIVEN TRACTION CARPETS IN GRAVEL-BED RIVERS

Estimate of stream-flow conditions

The examples from modern rivers discussed in the preceding section indicate that traction carpets occur as a transport mechanism in gravel-bed rivers. Moreover, the preservation of their inferred deposits in both modern and ancient streams is evidence that in certain flow conditions the carpets may be a more efficient transport mechanism than 'normal', low-density, grain-by-grain bedload.

In order to assess the mechanical feasibility of traction carpets in gravel-bed rivers, the stream-flow conditions required for carpet development are estimated in this section. A useful approach is to consider by palaeohydraulic techniques, the critical stream-flow conditions necessary for the entrainment of *individual* gravel clasts although it must be noted that such semi-quantitative analyses are fraught with difficulties (see Maizels, 1987 for recent review). Throughout this discussion, illustrative reference will be made to the thick Trabeg conglomerate sheets. The thickest, single, unamalgamated conglomerate units have a modal thickness of 0·4 m and a mean MPS (a-axis) of 0·1 m. Density of the gravel clasts and the smaller sand and silt particles is taken to be 2650 kg m^{-3}.

A rough estimate of the critical bed shear stress required for the entrainment of an individual clast on a gravel bed can be made by consideration of Shields' criterion (Baker & Ritter, 1975; Church, 1978):

$$\tau_c = \theta g (\rho_c - \rho_f) D \qquad (1)$$

where τ_c is the critical bed shear stress; θ is the dimensionless bed shear stress (Shields' function); ρ_c and ρ_f are the densities of the clast and the entraining flow respectively; and D is the intermediate diameter (b-axis) of the entrained clast. For any single clast, the critical shear stress is controlled by the Shields' function (θ) and the density of the fluid (ρ_f). The Shields' function is highly variable, ranging from 0·01 to 0·25 (Williams, 1983), and is dependent on the degree of sediment sorting, imbrication, packing, clustering of clasts and stream-bed armouring (Reid & Frostick, 1987; Maizels, 1987). The density of the entraining fluid is dependent on the concentration of sediment already suspended in the turbulent stream flow.

For large grain Reynolds Numbers when the clast projects out of the stream bed into the flow, the dimensionless Shields' function (θ) is roughly constant in the range 0·02 to 0·10, with an average of about 0·05 (Church, 1978; Costa, 1983; Lord & Kehew, 1987). For the modal Trabeg conglomerate sheets, the intermediate particle diameter (D) of the larger clasts may be taken as 0·08 m. Considering first a clear water stream flow of density 1000 kg m^{-3}, the average critical bed shear stress for entrainment for such a clast is 65 N m^{-2}.

Clast interaction on a static bed exerts an important control on the critical conditions required for clast entrainment (Brayshaw, 1984; Frostick & Reid, 1984; Reid & Frostick, 1987). Imbricated clusters of disc- and blade-shaped clasts (cluster bedforms, Brayshaw, 1984) stabilize the gravel bed. Reid & Frostick (1987) have shown that, for one natural stream, the bed shear stress required for gravel movement from a loosely clustered bed is up to two times greater than that required for movement from an open bed. Frostick & Reid (1984) suggest that infilling of the voids between gravel clasts with sand further strengthens the gravel bed, but Whiting *et al.* (1988) observed that infilling of voids actually *promoted* gravel bedload sheet movement. Taking these influences into consideration, a Shields' function of about 0·20 may be more appropriate for many situations, and the estimated critical bed shear stress may be up to four times larger (260 N m^{-2} for the Trabeg conglomerate sheets example).

The second control on the critical bed shear stress required for clast entrainment, as defined by Shields' criterion (equation 1), is the density of the stream flow (ρ_f). Natural, powerful streams will carry finer sand, silt and mud in suspension so that the density of the flow is dependent on the concentration of such a suspended load and is given by:

$$\rho_f = \rho_s C_s + \rho_w (1 - C_s) \qquad (2)$$

where C_s is the volume concentration of sand and finer suspended sediment; and ρ_s and ρ_w are the densities of sand (2650 kg m^{-3}) and water (1000 kg m^{-3}), respectively. Thus an increase in the suspended load is predicted to cause a proportional decrease in the critical bed shear stress required for clast entrainment. The bed shear stress applied by a flow may be given by:

$$\tau_f = g d \rho_f S \qquad (3)$$

where τ_f is the bed shear stress exerted by the flow; d is the depth; and S is the energy slope ($S = \tan\beta$, or $= \sin\beta$ for low slopes, where β is the angle of the local bed slope). Thus, fluid density also controls the magnitude of the shear stress actually exerted on the stream bed.

This highlights the significant effect that high sediment concentration, notably of suspended finer-grained fractions, has on the entrainment and transport of gravel in stream flows (see also Hampton, 1975; Gerson, 1977; Lord & Kehew, 1987; Bradley & McCutcheon, 1987).

Traction carpet development from low-density bedload

Stream-driven, high-density gravelly grain flows could be initiated in fluvial settings in two different ways, both of which are envisaged to be associated with high magnitude floods. The first possibility discussed here is the mechanism of overconcentration of normal (low-density) stream bedload.

The ambiguity of the distinction between low-density and high-density bedload has already been mentioned. Normal bedload is usually considered to involve grain-by-grain movement where fluid–solid momentum transfer is dominant. However, Bagnold's (1954, 1966) view of bedload envisages *some* solid-to-solid momentum transfer (see also Leeder, 1979). Therefore it appears appropriate to distinguish between this 'normal' bedload and high-density (traction carpet) bedload in which solid-to-solid momentum transfer is dominant. The definition of bedload type can probably not rely only on the dominant means of momentum transfer, and additional possible parameters for the distinction of low- and high-density bedloads and their deposits are listed in Table 1.

A gravelly traction carpet might be developed by piecemeal addition of clasts from the stream bed to a low-density bedload of rolling, sliding and saltating gravel during rising flood stage or possibly during falling flood stage in a flush flood (Pierson & Scott, 1985). The 'transport stage' of the sediment is defined as the ratio u_*/u_{*c} (Francis, 1973) where u_* is the shear velocity within the stream flow (a measure of the velocity gradient of the stream flow) and u_{*c} is the critical shear velocity required for particle entrainment. The fluid shear velocity, u_*, is given by:

$$u_* = \sqrt{\tau_f/\rho_f} \quad (4)$$

where τ_f is the fluid boundary shear stress; and ρ_f is the density of the fluid. At a transport stage of about two, normal grain saltation paths are interrupted by collisions and deflections (Leeder, 1979). With further increase in the stage, the concentration of the gravel in the bedload is such that inertial clast collisions become prevalent (Bagnold, 1956, 1966, 1973) and the high-density gravel carpet then corresponds to a stream-driven, gravelly 'grain flow' or traction carpet. The bed shear stress applied at a transport stage of four is estimated to be in the range of 728 to 2086 N m^{-2} for the Trabeg high-density stream-flow conglomerates example, depending on the ease of clast entrainment (see above).

The carpet, once initiated, is envisaged as a moving layer of gravel supported by dispersive pressure, buoyancy and by quasi-static grain-to-grain contacts due to the hindered settling effect (cf. Bagnold, 1954; 1973; Middleton, 1970; Hampton, 1979; Pierson, 1981; Postma *et al.*, 1988). The rheology of the moving carpet is expected to be that of a fluid, possibly Newtonian, at high shear rates, although at lower shear rates the carpet will change to a quasi-plastic as its yield stress limit is approached. The movement of the gravel carpet would not be continual, but is more likely to be non-uniform and unsteady and the deposits might reflect pulsatory 'freezing' (cf. Lowe, 1982).

In order to assess the conditions necessary to flow maintenance, consider a moving traction carpet in which gravel constitutes more than 50% of the volume of the flow, the rest being an interstitial mixture of poorly sorted sand and water (Fig. 7). The forces required for the entrainment and transport of the sand

Table 1. Possible distinctions between low-density and high density gravel bedload

Low-density bedload	High-density bedload (traction carpet)
Processes	
Fluid–solid momentum transfer dominant	Solid–solid momentum transfer dominant
Thin sheets, 1 or 2 grains thick	Thick sheets, 3 or more grains thick
Fluid rheology	Quasi-plastic with yield strength due to friction; fluid at shear rates
Turbulent flow behaviour	Laminar flow behaviour
Clasts supported by static grain-to-grain or grain-to-bed contacts	Clasts supported by buoyancy, dispersive pressure and static grain-to-grain contacts
Developed in low-magnitude perennial streams with low sediment concentrations	Developed in high-magnitude floods in ephemeral streams with high sediment concentrations
Products	
Thin sheets but can be amalgamated to form thicker units	Thick sheets but can be amalgamated to form thicker units
Framework- or matrix-supported	Framework- or matrix-supported
Moderate to good sorting	Poor to moderate sorting
Normal grading common	Inverse grading common
a (t) *b* (i) imbrication common	*a*(p) *a*(i) imbrication common

are ignored in this model, an approach that is considered valid because of the low bed shear stress required for sand movement compared to gravel (see also Lowe, 1976, p. 195).

Part of the weight of the gravel clasts in the carpet would be supported by buoyancy, enhanced by the dense nature of the sand/water matrix interstitial to the gravel clasts. It is first assumed that the buoyant lift is provided only by the displacement of the watery-sand matrix, according to Archimedes' principle, so that the effective weight of the gravel clasts in the carpet (W') is given by

$$W' = (\rho_c - \rho_m)\, g \cos\beta\, C_c\, h, \qquad (5)$$

where ρ_c and ρ_m are the densities of the clast and the matrix, respectively; C_c is the volume concentration of the clasts; h is the thickness of the traction carpet; g is the acceleration due to gravity; and β is the angle of the slope. For typical stream channels (slopes of $\beta < 5°$), $\cos\beta \rightarrow 1$ and equation (5) simplifies to:

$$W' = (\rho_c - \rho_m)\, g\, C_c\, h. \qquad (6)$$

The role of buoyant lift in the support of the clasts is, in this case, controlled by the bulk density of the sand/water matrix given by:

$$\rho_m = C_{mg}\,\rho_{mg} + (1 - C_{mg})\,\rho_w, \qquad (7)$$

where C_{mg} and ρ_{mg} are the concentration and density of sand, respectively and ρ_w is the density of water. The theoretical analysis of Rodine & Johnson (1976) shows that the volume concentration of cohesionless sand may be up to 95%, if the sand is poorly sorted. Greater concentrations give rise to particle interlocking, resulting in strong frictional effects. In natural conditions the interstitial matrix of the gravelly traction carpets is likely to be poorly sorted. For example, the matrix in the Trabeg sheet conglomerates is defined as everything from silt to small pebble grade (see Fig. 3a). Such a poorly sorted 'sand' matrix, if it is conservatively assumed to have a volume concentration of 80% during transport, would have had a density of 2320 kg m^{-3}.

As the density of the interstitial sand/water mixture approaches that of the gravel clasts in the carpet, the effective weight of the carpet is very much reduced. Thus, for a traction carpet 0·5 m thick (the modal thickness of the Trabeg conglomerate sheets) with 60 vol% clasts and 40 vol% of sand/water mixture ($\rho_m = 2320$ kg m^{-3}), the effective weight of the gravel clasts would be 970 N m^{-2}.

Hampton (1979) has argued that, in moving sediment flows, the buoyant lift is the product of not only the lift derived from the displacement by the clasts of the matrix, but also from an increase in pore pressure caused by the loading of the weight of the clasts onto the watery sand matrix. Thus the effect of buoyancy can be considered as the lift derived from the displacement by the gravel clasts of all the sediment in the carpet, including the gravel clasts themselves (Rodine & Johnson, 1976; Hampton, 1979; Pierson, 1981). Hence equation (6) is modified to:

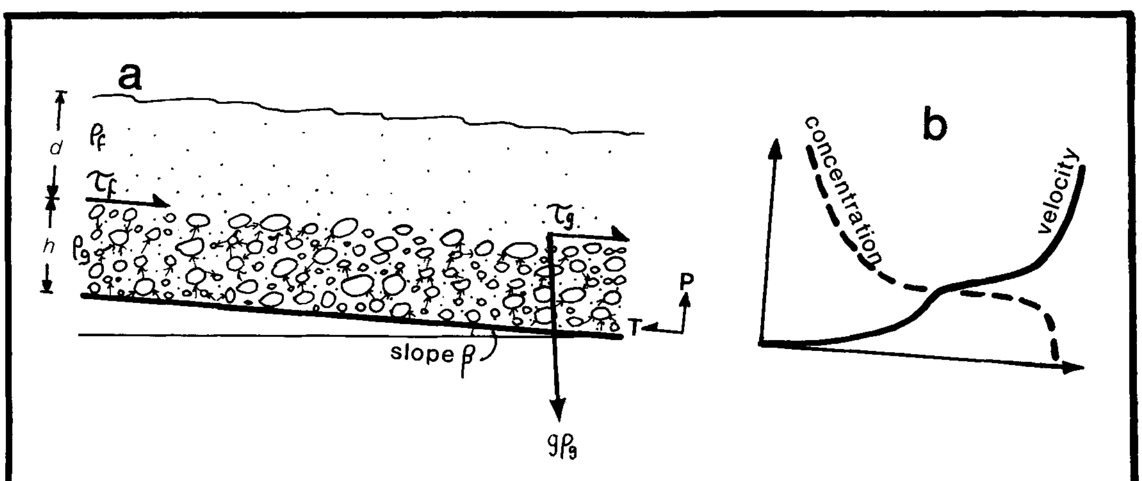


Fig. 7. Model for a typical current-induced density-modified gravel grain flow. (a) Schematic diagram indicating the definition of some of the terms used in the text; (b) predicted velocity and concentration profiles through the combined thickness of the decoupled fluidal and gravel flows (after Postma *et al.*, 1988).

$$W' = (\rho_c - \rho_g)\, g\, C_c\, h \tag{8}$$

where ρ_g is the bulk density of the gravel carpet given by:

$$\rho_g = C_c \rho_c + (1 - C_c)\, \rho_m. \tag{9}$$

For the Trabeg gravelly traction carpet modelled, the effective weight of the gravel clasts would then be 390 N m^{-2}.

The remaining part of the weight of the clasts, not supported by buoyant lift must be supported by dispersive pressure (Bagnold, 1954) at high shear rates, and quasi-static grain-to-grain contacts at low shear rates (Pierson, 1981) in order for the traction carpet to be mobile (Postma *et al.*, 1988). Bagnold (1954, 1966, 1973) showed that the tangential shear stress (T) applied to a normal grain flow is related to dispersive pressure (P) by:

$$T/P = \tan \alpha, \tag{10}$$

where α is the dynamic angle of internal friction. He argued that

$$\tan \alpha = \tan \varphi, \tag{11}$$

where $\tan \varphi$ is the static frictional coefficient. Bagnold (1973) concluded that a value of $\tan \varphi = 0{\cdot}63$ may be taken for natural, uniform quartz solids, although it is not known how accurate this value is for the type of gravelly material discussed here. It is intuitively expected that a sand matrix, acting like ball bearings, will reduce the effective friction between gravel clasts (see also Whiting *et al.*, 1988). Rodine & Johnson (1976) have shown that the frictional strength of granular substances, controlled by $\tan \varphi'$, the effective coefficient of friction, can be very low so long as the concentration of the coarser solids is less than 50 vol%, or if the material is poorly sorted. It is also been shown that the bulk friction factor of a moving sediment water mixture decreases as the sediment concentration increases (e.g. Newitt *et al.*, 1955; Savage, 1979). Thus, paradoxically, the bulk friction factor, the principal control of the yield stress limit of cohesionless sediment, will decrease as a slowing, shearing traction carpet tends to collapse. Because of this decrease in friction, a traction carpet is predicted to remain mobile even when the applied stresses that drive the carpet are comparatively low. Therefore, the effective weight of the gravel clasts in the fraction carpet (W') must be balanced by the dispersive pressure (i.e. $P = W'$) so that:

$$T = W' \tan \varphi', \tag{12}$$

where $\tan \varphi'$ is taken to be a value $\leq 0{\cdot}63$ (and probably $\ll 0{\cdot}63$).

Two shear stress components act on the gravelly traction carpet: the shear stress due to the downslope component of the weight of the carpet (τ_g) and the bed shear stress exerted by the superjacent turbulent stream flow (τ_f). The latter shear stress is given by equation (3) (for similar usage see Hiscott & Middleton, 1979; Hein, 1982; Postma *et al.*, 1988), and Leeder (1979) has shown that this stress is expected to act throughout the carpet. The former shear stress (τ_g) is estimated according to the formula (Middleton & Southard, 1978):

$$\tau_g = \rho_g\, g\, h \sin \beta. \tag{13}$$

These two shear stress components combine to drive the traction carpet, so that:

$$\tau_t = \tau_g + \tau_f = g \sin \beta\, (\rho_g\, h + \rho_f\, d). \tag{14}$$

That the two applied shear stresses are sufficient (i.e. $\tau_t = T$) to drive a traction carpet in a stream flow on a low-gradient slope can be shown by consideration of the example of the Trabeg conglomerate sheets. The 0·5 m-thick, gravelly traction carpet discussed above could be maintained mobile at the base of a 2 m-deep stream flow of a sand-laden turbulent suspension with a density of 1495 kg m^{-3} (i.e. 30 vol% sand), moving on a stream floor inclined at less than 1° ($\tan \varphi' = 0{\cdot}63$). Such physical conditions are easily attainable in nature, notably on stream-dominated, 'flashy' alluvial fans and on proglacial outwash fans. High sediment concentrations in the stream would seem to promote high-density bedload movement. If $\tan \varphi'$ is taken as a value less than 0·63, as suggested by the experiments of Rodine & Johnson (1976), then the conditions for traction carpet movement are even more easily attained.

Traction carpet development by suspension settling

In high magnitude stream floods gravel, together with sand and silt fractions, may be entrained rapidly into suspension within a stream flow (Baker, 1984). It was demonstrated above that the entrainment of gravel clasts is influenced by the density of the stream flow, which is controlled by the concentration of suspended sediment. Similarly, the suspension of gravel clasts is also influenced by stream-flow density. This effect can be demonstrated by consideration of an approximate criterion for suspension (Bagnold, 1966):

$$v_g / u_* < 0{\cdot}8, \tag{15}$$

where v_g is the fall velocity of the grain in an otherwise grainless stationary fluid. Increased concentration of sediment in the stream will reduce the effective fall velocity (v'_g) of the grains in the flow, due to hindered settling by mutual deflections and impacts according to the criterion proposed by Richardson & Zaki (1968) for stationary fluids:

$$v'_g = v_g (1 - C)^a, \tag{16}$$

where C is the concentration of the grains in the falling dispersion and a is an exponent dependent on the grain Reynolds Number. Rewriting equation (15) as:

$$v'_g / u_* < 0{\cdot}8, \tag{17}$$

it can be concluded that the entrainment and suspension of grains become progressively easier as the stream-flow stage rises and the concentration of suspended load increases (see Bradley & McCutcheon, 1987 for further discussion).

At the peak of such a high magnitude high density flood, all particles, except perhaps the largest entrained, will be in a state of intermittent or continual suspension. When the shear velocity becomes constant or begins to decrease, the gravel will settle out into a more concentrated dispersion at the base of the flow. Two possibilities exist for the evolution of this basal dispersion. Firstly, the dense dispersion, although it may have a sharp rheological boundary with the overlying lower-density flow, may not underlie a true tractional phase (Postma *et al.*, 1988). In this case the gravel dispersion is merely a more concentrated, more viscous and slower moving part of the flowing turbulent suspension in the stream (see also Einstein & Chien, 1958 and Coleman, 1969 for reports of similar concentrated basal layers in flowing sandy suspensions). In such a dispersion, clast settling is hindered by mutual collisions (Richardson & Zaki, 1968), but the actual clast support is still mainly due to buoyancy and turbulence. If the dispersion collapsed and froze, the resulting deposit would be predicted to be normally graded or ungraded, poorly sorted, with a comparatively disorganized clast fabric. Some of the thickest, coarsest conglomerates of the Trabeg Conglomerate Formation, which have disorganized clast fabrics, could have been deposited in this manner.

Secondly, the gravel dispersion could become completely decoupled from the overlying turbulent stream flow. The layer would now be affected by the shear stress exerted by the overriding flow, as well as the downslope component of the weight of the layer. Turbulence in the gravel carpet is suppressed with increased concentration, the flow becomes laminar, and clast support is provided by buoyancy, dispersive pressure and hindered settling. The gravel layer then corresponds a traction carpet inferred by Lowe (1982) to form at the base of high density turbidity currents. These carpets formed by suspension settling would be driven in the same way as carpets formed by overconcentration of low density bedload discussed above. The mechanism is suggested also to occur in high-density stream floods (see also Nemec & Muszyński, 1982), and may be most appropriate for the modern examples cited by Scott & Gravlee (1968), Foley *et al.* (1978) and Mears (1979). The thick Trabeg conglomerate sheets typically have erosive bases. This suggests that the stream floods responsible for the deposition of those units also involved an initial erosive, macro-turbulent phase from which the traction carpets were developed by suspension settling.

Traction carpet cessation and preservation

A number of factors may cause the cessation of stream-driven traction carpets. In general, a decrease in flow depth and/or a downstream lowering of the channel slope will cause a decrease in the applied shear stress. Thus, the boulder front of one of the gravelly 'underflows' described by Scott & Gravlee (1968) occurs where there is a reduction in depth of the Rubicon River, associated with the expansion of the reach and reduction in slope. The traction carpets will have a critical thickness controlled by the magnitude of the applied shear stress. A decrease in the shear stress beyond the critical magnitude required for flow maintenance or overthickening of the carpet by addition of sediment to the top will cause collapse and freezing (Lowe, 1982). With highest magnitude floods the amalgamation of traction carpets is likely to occur by initiation, movement and freezing of successive carpets to accumulate gravel units significantly thicker than an average constituent carpet (cf. Lowe, 1982).

On cessation, a traction carpet will be susceptible to reworking by low density, grain-by-grain bedload movement. The deposition of the traction carpets in modern streams (e.g. Scott & Gravlee, 1968) and their inferred presence in ancient alluvial deposits (e.g. Nemec & Muszyński, 1982; this paper) indicate that the bed shear stress applied by the stream flow on cessation of the traction carpet is less than that required for the entrainment of individual clasts from the top of such gravel deposits. This implication suggests that relatively low shear stresses are required for the maintenance of a moving traction carpet, lower than that required for movement of individual clasts (cf. Newitt *et al.*, 1955), particularly if the clasts in the traction carpet are large.

In the Trabeg conglomerate sheets, some limited reworking of the tops of the gravel layers may be marked by the inclusion of small pebbles at the base of the sandstones that drape the conglomerates (Fig. 2). Thus, it is considered that the waning stream flow did not have sufficient power to significantly rework the frozen, large pebble to cobble grade traction carpets.

SUMMARY AND CONCLUSION

The principal conclusion of this paper is that high-density flood flows in fluvial channels are capable of developing and driving decimetre- to possibly metre-thick, non-turbulent gravelly traction carpets (rheologically comparable to density-modified grain flows) along the channel floor. Such traction carpets may be driven mainly by the shear stress exerted by the superjacent, fast-flowing turbulent stream flow at a flood–peak stage. This tangential shear stress is converted to dispersive pressure which supports much of the weight of the clasts within the flow, in addition to the support derived from the buoyant lift enhanced by the dense nature of the interstitial fluid of watery sand.

Semi-quantitative modelling suggests that for traction carpet initiation, even in high-density stream flows, a shear stress about four times larger than that required for entrainment of individual clasts is necessary. Consideration of the available observations and theory shows, however, that once initiated, the gravelly traction carpet requires a much smaller shear stress for flow maintenance. Traction carpets, particularly poorly sorted and coarse-grained ones, can move in relatively shallow streams on a comparatively low gradient. The deposits of stream-driven gravelly traction carpets are most likely to accumulate in higher-gradient streams which carry a high concentration of sediment probably during high-magnitude flash floods.

Stream-driven traction carpets are predicted to produce sheet-like units of mainly clast-supported gravel that may have erosive bases. The units might be ungraded or inversely graded, or perhaps contain inverse-normal grading. Individual beds, formed by single traction carpets in the most powerful stream flows, might range in thickness from a few decimetres up to a few metres thick. Thick beds may also be the result of amalgamation of thinner carpets. The possible examples of such modern (e.g. Mears, 1979) and ancient (e.g. Nemec & Muszyński, 1982) alluvial deposits are here supplemented by the analysis of the conglomerate sheets of the Trabeg Formation which are thought to have been emplaced by high density stream floods on a stream-dominated alluvial fan.

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