SEDIMENT GRAVITY FLOWS: II. DEPOSITIONAL MODELS WITH SPECIAL REFERENCE TO THE DEPOSITS OF HIGH-DENSITY TURBIDITY CURRENTS[1]

DONALD R. LOWE
Department of Geology
Louisiana State University
Baton Rouge, Louisiana 70803

ABSTRACT: Four principal mechanisms of deposition are effective in the formation of sediment gravity flow deposits. Grains deposited by *traction sedimentation* and *suspension sedimentation* respond individually and accumulate directly from bed and suspended loads, respectively. Those deposited by *frictional freezing* and *cohesive freezing* interact through either frictional contact or cohesive forces, respectively, and are deposited collectively, usually by plug formation. Sediment deposition from individual sediment flows commonly involves more than one of these mechanisms acting either serially as the flow evolves or simultaneously on different grain populations.

Deposition from turbidity currents is treated in terms of three dynamic grain populations: 1) clay- to medium-grained sand-sized particles that can be fully suspended as individual grains by flow turbulence, 2) coarse-grained sand to small-pebble-sized gravel that can be fully suspended in large amounts mainly in highly concentrated turbulent suspensions where grain fall velocity is substantially reduced by hindered settling, and 3) pebble- and cobble-sized clasts having concentrations greater than 10 percent to 15 percent that will be supported largely by dispersive pressure resulting from clast collisions and by buoyant lift provided by the interstitial mixture of water and finer-grained sediment. The effects of hindered settling, dispersive pressure, and matrix buoyant lift are concentration dependent, and grain populations 2 and 3 are likely to be transported in large amounts only within flows having high particle concentrations, probably in excess of 20 percent solids by volume. Low-density turbidity currents, made up largely of grains of population 1, typically show an initial period of traction sedimentation, forming Bouma T_b and T_c divisions, followed by one of mixed traction and suspension sedimentation (T_d), and a terminal period of fine-grained suspension sedimentation (T_e).

The sediment loads of high-density turbidity currents commonly include grains belonging to populations 1, 2, and 3. Consequently, deposition often occurs as a series of discrete sedimentation waves as flows decelerate and individual grain populations can no longer be maintained in transport. Each sedimentation wave tends to show increasing unsteadiness and accelerating sedimentation rate as it evolves, passing from an initial stage of traction sedimentation, to one of mixed frictional freezing and suspension sedimentation within traction carpets, to a final stage of direct suspension sedimentation. Sequences of sedimentary structure divisions representing this succession of depositional stages are here termed the R_{1-3} sequence, representing population 3 grains, and the S_{1-3} sequence, representing population 2. Deposition of the high-density suspended load leaves behind a residual low-density turbidity current composed largely of population 1 grains. At their distal ends, high-density turbidity currents deposit mainly by suspension sedimentation, forming thin S_3 divisions. These S_3 divisions are the same as Bouma T_a and, if subsequently capped by T_{b-e} deposited by the residual low-density flows, become the basal divisions of normal turbidites.

Liquefied flows deposit by direct high-density suspension sedimentation. Grain flows of sand are characterized by frictional freezing and their deposits are limited mainly to angle-of-repose slipface units. Density-modified grain flows, in which larger clasts are partially supported by matrix buoyancy, and traction carpets, in which a dense frictional grain dispersion is driven by an overlying turbulent flow, are important in the buildup of natural deposits on submarine slopes. Cohesive debris flows depost sediment mainly by cohesive freezing, commonly modified by suspension sedimentation of the largest clasts.

INTRODUCTION

A reasonably clear picture has emerged in recent years of the gravity-driven processes that deliver and redistribute coarse sediment in the deep sea. The most important of these processes have been termed sediment gravity flows or sediment flows (Middleton and Hampton, 1973). Middleton and Hampton (1973, 1976) recognize four main end-member flow types based on the mechanisms by which the larger transported grains are supported above the bed. More recently Lowe (1979b) and Nardin et al. (1979) have suggested a classification and nomenclature based on both

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flow rheology (fluid vs. plastic behavior) and particle support mechanism (Figs. 1 and 2).

In their development of sediment flow deposit models, Middleton and Hampton (1973, 1976) rely largely on the results of experimental studies and on field observations of the textures and structures of natural deposits. Although their results are adequate for low-density turbidity currents and cohesive debris flows, which have been the subject of considerable experimentation and field investigation, much new evidence suggests that modifications are required of their grain, liquefied, and fluidized flow models. The grain flow depositional model of Middleton and Hampton (1973, 1976) derives mainly from studies of inferred grain flow deposits by Stauffer (1967) and from theoretical and experimental results of Bagnold (1954, 1956). Subsequent examination of the beds studied by Stauffer (Van der Kamp et al., 1973; Link, 1975) suggest that they are turbidites, and theoretical reasoning indicates that sandy grain flows will generally be less than 5 cm thick (Lowe, 1976a). Liquefied flows (=fluidized flows of Middleton and Hampton, 1973, 1976) remain largely unstudied, but some evidence suggests that their deposits may show a range of distinctive textures and structures (Lowe, 1976b). Also, Middleton and Hampton (1973, 1976) do not consider high-density turbulent flows although many workers have suggested their importance in depositing so-called proximal deep-sea sands (Kuenen, 1950; Fisher and Mattison, 1968; Middleton, 1967, 1970; Chipping, 1972; Corbett, 1972; Hiscott and Middleton, 1979).

FLOW BEHAVIOR	FLOW TYPE		SEDIMENT SUPPORT MECHANISM
FLUID	FLUIDAL FLOW	TURBIDITY CURRENT	FLUID TURBULENCE
		FLUIDIZED FLOW	ESCAPING PORE FLUID (FULL SUPPORT)
		LIQUEFIED FLOW	ESCAPING PORE FLUID (PARTIAL SUPPORT)
PLASTIC (BINGHAM)	DEBRIS FLOW	GRAIN FLOW	DISPERSIVE PRESSURE
		MUDFLOW OR COHESIVE DEBRIS FLOW	MATRIX STRENGTH MATRIX DENSITY

FIG. 1.—Nomenclature of laminar sediment gravity flows based on flow rheology and particle support mechanisms (Lowe, 1979b).

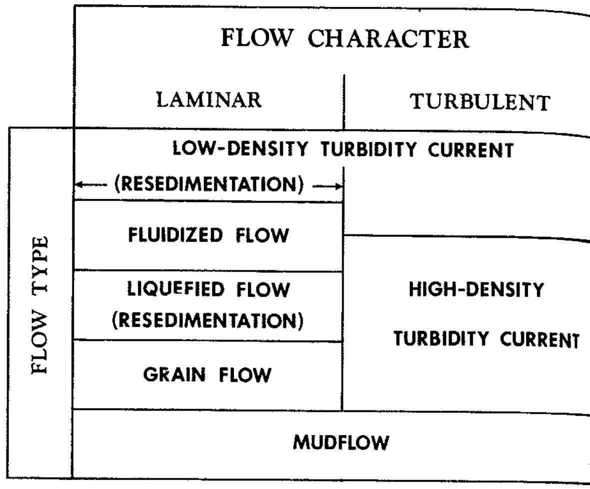

FIG. 2.—Nomenclature of both laminar and turbulent sediment gravity flows (Lowe, 1979b).

The properties of a sedimentary deposit largely reflect the process by which it was deposited and may not be related to the sediment transport history. Accordingly, sediment gravity flows are here evaluated in terms of end-member depositional processes. From this evaluation, involving both theoretical and empirical considerations, conceptual models of major sedimentation units are developed and compared with natural deposits.

FLOW TYPES AND DEPOSITIONAL MECHANISMS

The end-member types of sediment gravity flows are shown in Figures 1 and 2. Based on their rheology, sediment-fluid mixtures exhibit either fluid or plastic behavior, and the corresponding flows are termed fluidal and debris flows, respectively. These two broad rheological groups can then be further subdivided into individual flow types based on the primary mechanism by which larger sedimentary grains are maintained above the bed (Fig. 1): *turbidity currents* in which the sediment is supported by flow turbulence; *fluidized flows* in which the sediment is fully supported by upward moving pore fluid; *liquefied flows* in which the sediment is not fully supported but is settling through the pore fluid which is displaced upward; *grain flows* in which the sediment is supported by dispersive pressure arising from particle collisions; and *cohesive flows* in which the sediment is supported by a cohesive matrix.

The mechanics of sediment flows have been reviewed by Middleton (1966, 1967, 1969, 1970), Middleton and Hampton (1973, 1976), Nardin et al. (1979), and Lowe (1979b) and will not be discussed here.

Sediment transported in decelerating sediment flows is deposited by two basically different mechanisms. From fluidal flows, particles tend to accumulate individually, either from the bed-load layers (*traction sedimentation*) or directly from the suspended loads (*suspension sedimentation*). The deposits (Figs. 3A and 3B) are formed progressively from the

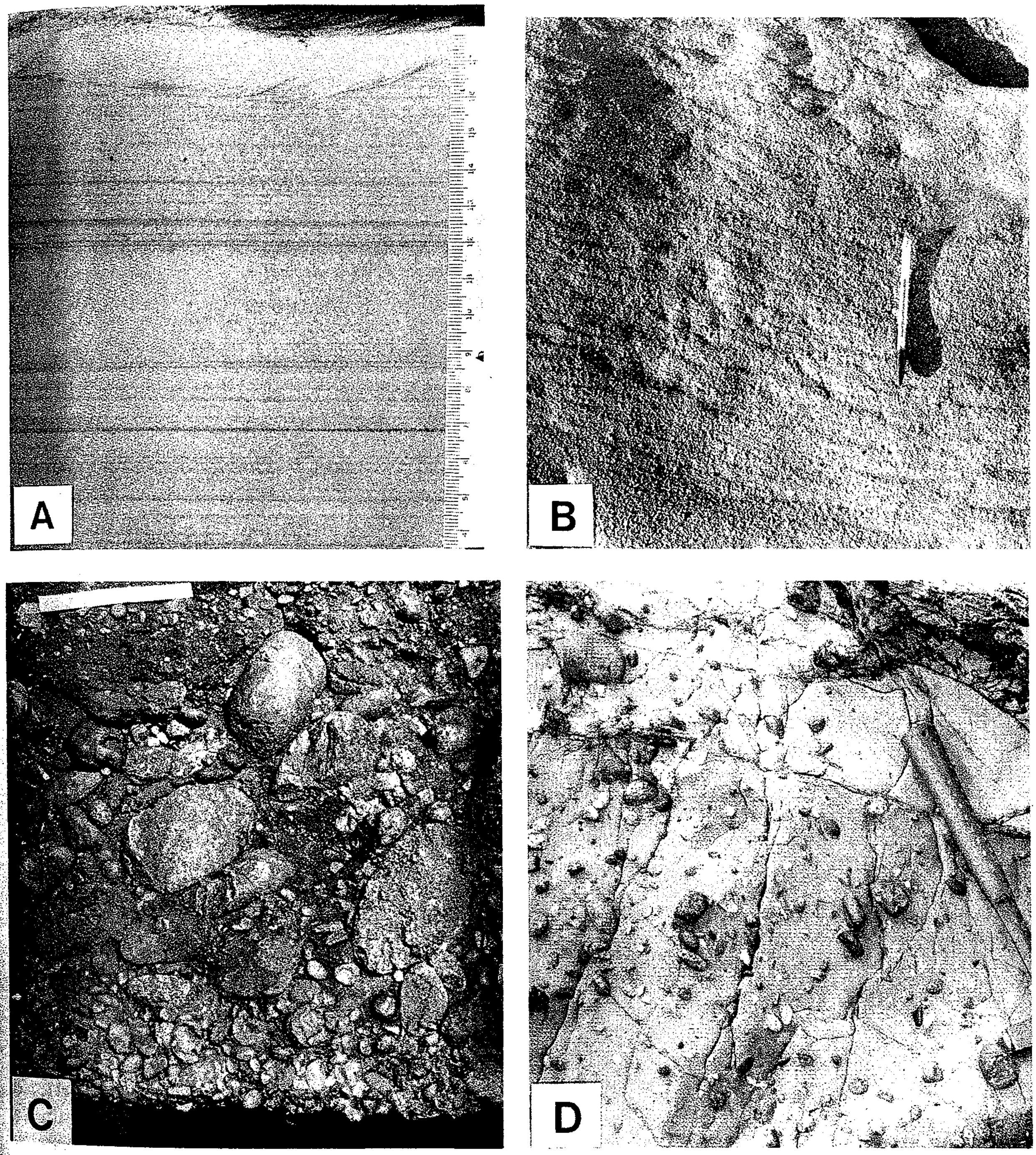

FIG. 3.—Summary of the characteristics of deposits formed by the four basic sedimentation mechanisms. A) Turbidite flat lamination (Bouma T_b) and cross-lamination (T_c) formed by traction sedimentation. Scale in mm. B) Coarse-grained sandstone showing dish structures, increasing in concavity upward, and pillar structures, increasing in abundance upward, deposited by the direct sedimentation of a coarse-grained high-density suspension. C) Inversely graded conglomerate deposited by frictional freezing. Scale is 1 foot long. D) Matrix-supported pebbly mudstone formed by cohesive freezing.

base upward. Debris flows deposit sediment as the applied shear stress drops below the yield strength of the moving material. The flows freeze inward either en masse or from corners and free surfaces, inward and downward, respectively (Johnson, 1970), as a consequence of frictional grain resistance (*frictional freezing*) and/or cohesive grain interactions (*cohesive freezing*). The basic characteristics of the deposits of each of these mechanisms is summarized in Figure 3. Figure 4 shows the inferred relationships among sediment gravity flow types and depositional mechanisms.

DEPOSITIONAL MODELS

Turbidity Currents

Turbidity currents are sediment flows in which the grains are suspended by turbulence. Observations of sediment-flow deposits, especially those of Walker (1975, 1977, 1978), experimental studies of sediment transport and deposition (Bagnold, 1954; Middleton, 1967; Shook et al., 1968; Govier and Aziz, 1972), and consideration of the general mechanics of sediment movement indicate that deposition of sediment from turbidity currents must be treated in terms of several grain-size populations. This is required because individual particle size groups within the same flow are commonly held above the bed by somewhat different support mechanisms and may be deposited during discrete sedimentation waves as the relative efficacy of these mechanisms changes with flow deceleration.

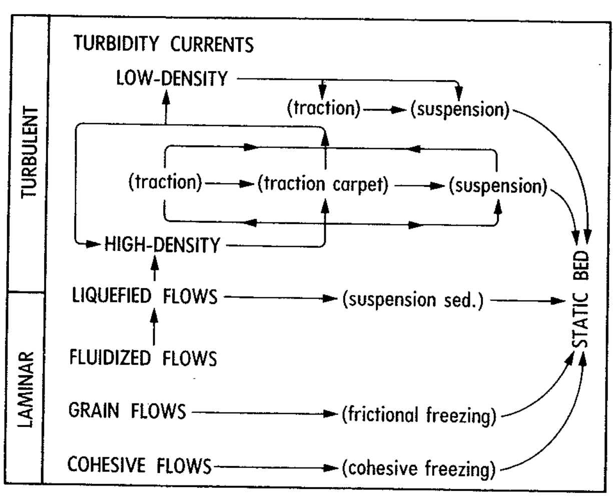

FIG. 4.—Summary of the principal sedimentation mechanisms of sediment gravity flows. Traction carpet sedimentation, discussed in the text, represents a special form of frictional freezing.

Three main particle grain-size populations can be identified. 1) Clay, silt, and fine- to about medium-grained sand-size particles can be maintained in suspension by fluid turbulence alone, largely independent of their concentration; hence, dilute, low-density flows are possible (Pantin, 1979). 2) Coarse-grained sand to small-pebble-sized gravel will not be fully suspended in large amounts within dilute flows (Pantin, 1979). In concentrated suspensions having a wide range of particle sizes, these coarser grains can be supported by the combined effects of i) turbulence, ii) hindered settling resulting from their own high concentration, and iii) the buoyant lift provided by the interstitial mixture of water and finer-grained sediment. 3) Pebble- and cobble-sized clasts having concentrations greater than 10 percent to 15 percent will be supported by the combined effects of fluid turbulence, hindered settling, matrix buoyant lift, and dispersive pressure resulting from grain collisions. The effects of hindered settling, dispersive pressure, and matrix buoyant lift are directly related to grain concentration. As a result, grain populations 2 and 3 are likely to be transported in large quantities only in relatively concentrated flows and will tend to be deposited rapidly once sedimentation begins and particle concentration decreases.

In the following discussion, therefore, two principal types of turbidity currents will be considered: low-density flows made up largely of population 1 grains and in which sediment support is largely independent of particle concentration; and high-density flows, which can include populations 1, 2 and 3, in which particle support is dependent on concentration-related effects. Although empirical documentation of the differences between low- and high-density turbidity currents is not available, results of Middleton (1966, 1967), Bagnold (1954), Wallis (1969), and many others suggest that the effects of hindered settling and dispersive pressure become efficient in particle support mainly at grain concentrations above 20 percent to 30 percent. Hence, high-density flows of population 2 and 3 grains probably involve particle concentrations above these values. Flows of these coarse-grain populations having particle concentrations below 20 percent are probably unstable and, if formed, would tend to collapse en masse unless extremely turbulent. Flows composed of population 1 grains, whose support is largely independent of concentration, may be stable over virtually the entire range of possible grain concentration. The distinction between low- and high-density flows of fine-grained cohesionless sediment may thus be arbitrary.

Low-Density Turbidity Currents.—Deposition from low-density turbidity currents and the structuring of the resulting deposits have been extensively discussed and will not be reviewed in detail here (Bouma, 1962; Walker, 1965; Sanders, 1965; Middleton, 1967, 1969, 1970; Walton, 1967; Allen, 1970; Middleton and Hampton, 1973, 1976). Deceleration is marked by the passage of sediment from suspended to bed loads and subsequent deposition by traction sedimentation to form the Bouma T_b and T_c divisions (Fig. 3A). The overlying T_d reflects more direct suspension sedimentation but with some traction or near-bed effects before or during deposition to produce the fine lamination and textural sorting characteristic of this division (Walker, 1965; Hesse and Chough, 1981). T_e is formed by direct suspension sedimentation of the finest sediment.

Standing wave laminations, antidune cross-stratification, and higher-velocity traction structures are uncommon in turbidites, but their presence locally indicates that, when the corresponding bedforms are developed during deposition, they produce distinctive preservable laminations (Skipper, 1971; Skipper and Middleton, 1975). Other than the common occurrence of the T_a division below T_b, there is no experimental or theoretical evidence indicating that T_a forms by high-velocity traction sedimentation, and experimental results suggest that it is deposited by direct suspension sedimentation from high-density flows (Middleton, 1967). Hence, the T_a division is not considered here to belong in the sequence of structures deposited by low-density turbidity currents.

High-Density Turbidity Currents.—High-density turbidity currents have been the subject of discussion and speculation since proposed by Kuenen (1950, 1951). Although their mechanics remain largely conjectural, a considerable body of indirect evidence suggests that high-density turbulent flows of essentially cohesionless grains are effective in transporting and depositing sediment in the deep sea. This evidence includes the gross similarity between many ancient deep-sea deposits, especially so-called "proximal" turbidites, and deposits formed by small-scale experimental high-density flows (Middleton, 1967); observations that many sedimentary structures and textures in ancient deep-sea deposits seem to have formed by deposition from concentrated, turbulent suspensions (Walker, 1978); and inferences that turbulence may commonly develop after failure in slumps, slides, and liquefied flows (van der Knaap and Eijpe, 1968; Bjerrum, 1971; Lowe, 1979b).

High-density turbidity currents will here be subdivided into sandy flows, dominated by population 2 grains supported mainly by turbulence and hindered settling, and gravelly flows containing population 3 grains supported in large part by dispersive pressure and matrix buoyant lift.

Sediment Deposition from Sandy High-Density Turbidity Currents.—In the simplest high-density turbidity flows, the bulk of the suspended load consists of population 1 and 2 clay-, silt-, and sand-sized material with little or no sediment coarser than granules or small pebbles. Dispersive pressure can probably be neglected as a support mechanism in such flows, except possibly at their bases where shear rates are highest (Middleton, 1967; Lowe, 1976b).

Sediment deposition from a coarse-grained sandy high-density turbidity current can be traced through three main stages: I) a traction sedimentation stage, II) a traction-carpet stage, and III) a suspension-sedimentation stage. This sequence reflects increasing flow unsteadiness and collapse of the high-density suspended-sediment cloud.

I) A slightly unsteady but fully turbulent sandy high-density turbidity current will deposit some of its load to form a sand bed. Flow interaction with this bed can produce bedforms like those developed beneath low density flows, including both plane beds and dune-like features (Smith, 1955; Newitt et al., 1955; Sinclair, 1962; Govier and Aziz, 1972), although flow unsteadiness may often prevent the evolution of highly organized dunes. Sediment deposited under these conditions will show corresponding traction-sedimentation structures, mainly flat lamination and oblique or cross-stratification. The former is common within many thick "proximal" sandstone and pebbly sandstone units in deep-sea sequences (Mutti and Ricci-Lucchi, 1972, 1975; Middleton and Hampton, 1976; Aalto, 1976; Walker, 1978), although it is clear that not all flat lamination in these sequences was formed by traction sedimentation (Hiscott and Middleton, 1979). Cross-stratification, not including that developed at the tops of "proximal" sedimentation units (Allen, 1970; Cas, 1979), is reported from the bases of some units (Walker, 1978) (Fig. 5a) and from within others (Mutti and Ricci-Lucchi, 1972; Aalto, 1976). At this stage the current may also be locally erosive, and the deposits show lenticularity, amalgamation, and scour (Walker, 1978) (Fig. 5A).

II) As flow unsteadiness increases, the suspended sediment load becomes progressively concentrated toward the bed. The vertical heterogeneity within the suspended load is particularly marked in the coarser size grades (Smith, 1955; Spells, 1955; Newitt, Richardson, and Shook, 1962). As the concentration of coarse particles near the bed rises, transport in the bed-load layer becomes increasingly dominated by grain collisions (Bagnold, 1956; Shook and Daniel, 1965; Shook et al., 1968)

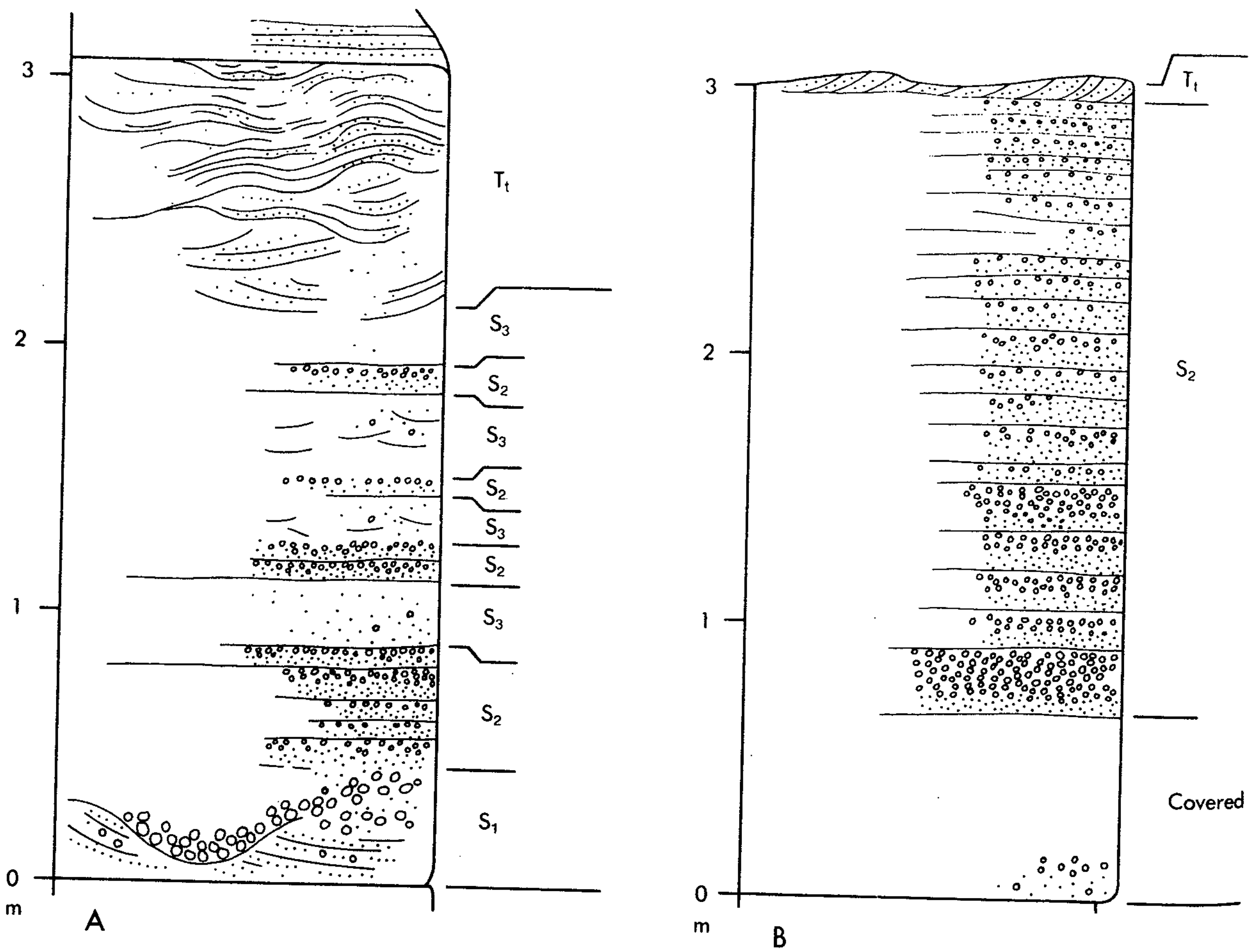

FIG. 5.—Thick-bedded "proximal" turbidites in the Thunderhead Sandstone of the Ocoee Supergroup, Great Smoky Mountains National Park, showing well-developed traction carpet deposits. Divisions of high-density (S_{1-3}) and low-density (T) depositional stages indicated to the right of each column. A) Sedimentation unit including divisions deposited by both high-density(S) and low-density (T) turbidity currents. Lowest division (S_1), composed of very coarse-grained sandstone to small-pebble conglomerate, shows traction structures and internal scour. The overlying coarse-grained sandstone to granule conglomerate is made up of alternating inversely graded traction-carpet layers (S_2) and massive or dish-structured suspension sedimentation deposits (S_3). The uppermost divisions, composed of medium- to fine-grained sandstone, show deformed flat lamination and large-scale cross-stratification, probably deposited by the residual turbidity current remaining after sedimentaton of the coarse high-density load. These divisions above S_3, here informally designated T_t to indicate the presence of traction structures, commonly include T_b flat lamination and large-scale cross-stratification not part of the normal Bouma sequence. B) Thick sedimentation unit deposited largely by traction carpets. The top has been reworked by the residual turbidity current to form large-scale cross-stratification.

leading to the formation of a basal particle layer maintained by dispersive pressure and fed by the rain of coarse-grained material from above. If turbulence is suppressed in this layer, as seems likely in dispersions maintained largely by dispersive pressure (Bagnold, 1956), it is a traction carpet in the sense of Dzulynski and Sanders (1962, p. 88). The occurrence of successions of inversely graded coarse-grained sand to granule layers in the lower parts of some proximal turbidites (Hiscott and Middleton, 1979) (Figs. 5 and 6) suggests that when "forced" by continued sediment fallout from the overlying flow, such traction carpets will collapse and freeze, and new carpets reform in succession at the rising bed surface.

Sedimentary units deposited by traction carpets developed beneath turbidity currents are common in "proximal" turbidites and T_a divi-

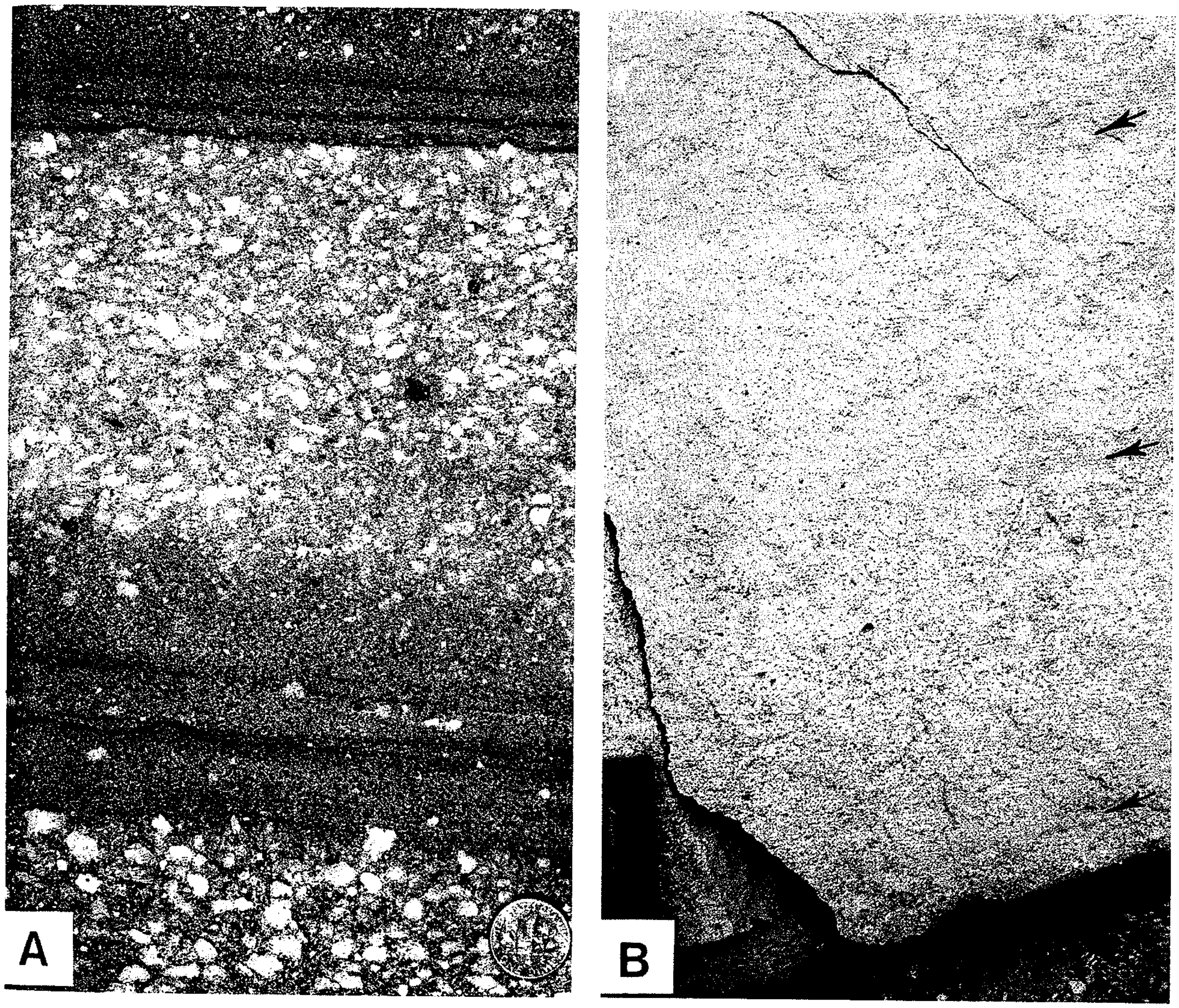

FIG. 6.—Traction carpet deposits. A) Well-developed conglomeratic traction carpet layers in the upper Precambrian Thunderhead Sandstone, Great Smoky Mountains National Park, Tennssee. Multiple basal shear laminations are overlain by thin zones of inversely graded fine- to coarse-grained sandstone containing widely dispersed granules. Uppermost inversely graded zone passes upward into massive, unstructured, poorly sorted sandy granule conglomerate deposited by direct suspension sedimentation. The presence of several shear laminations and overlying thin inversely graded zones suggests that, as the finest grains migrated to the base of the traction carpet, they become unable to generate sufficient dispersive pressure to support the overlying sediment column. Instead of the entire traction carpet freezing, the basal-fined-grained layer was deposited and the basal shear zone shifted to a slightly higher level in the carpet. B) Traction carpet layers in a Bouma T_a division in the Annot Sandstone from the Peira-Cava area of southern France (Bouma, 1962). Faint shear laminations (arrows) are overlain by thin inversely graded fine- to coarse-grained traction carpet zones that are in turn overlain by thick, massive layers of poorly sorted very coarse-grained to coarse-grained sandstone deposited by suspension sedimentation. Successive suspension-sedimentation layers are finer upward.

sions of normal turbidites. Examples include those described and interpreted by Hiscott and Middleton (1979) and others observed by the author in coarse-grained to conglomeratic flysch in the Precambrian Thunderhead Sandstone in the Southern Appalachian Mountains (King, 1964) (Figs. 5 and 6A) and within many coarse-grained T_a divisions in the Tertiary Annot Sandstone in the Peira-Cava area of southern France (Fig. 6B). In the Thunderhead Sandstone, traction-carpet deposits occur in 1- to 10-m-thick "proximal" turbidites. If not present at the bases of individual sedimentation units, they are generally underlain by zones of crude flat lamination or cross-stratification deposited during preceding stages of traction sedimentation (Fig. 5A). Individual traction carpet sedimentation units are from 5 to 15 cm thick (Fig. 6A). Each includes one or more dark, micaceous shear laminations near the base, a middle zone showing well-developed but discontinuous inverse grading from medium-grained sandstone to granule conglomerate, and an upper zone of massive, ungraded granule conglomerate. The inferred origin of these units by the freezing of traction carpets is summarized in Fig. 7.

There is a general direct relationship between grain size and the thickness of traction carpet layers indicating that the thickness of traction carpets, like that of true grain flows, is directly proportional to particle diameter (Bagnold, 1954; Lowe, 1976a).

III) At higher suspended-load fallout rates, there is insufficient time for development of either a bed-load layer or an organized traction carpet, and deposition is by direct suspension sedimentation (Walker, 1978). The deposition of a dense cohesionless suspension can be described in terms of a liquefied bed (Wallis, 1969). Settling grains accumulate directly until the rising surface of the static bed coincides with the top of the falling cloud. The resulting deposit is grain-supported and lacks traction structures. It can be massive or show size grading and/or primary water-escape structures developed during mass settling. Grading, if present, may be developed throughout the bed, or only at the base or top, and can range from distribution grading (Middleton, 1967), if late-stage turbulence has retarded deposition of the finer size grades, to coarse-tail grading, if the sediment cloud has settled as a non-turbulent suspension. The most common water-escape structures in such beds are dish and pillar structures (Figs. 3B and 9A). Deposits formed by the direct sedimentation of dense suspensions are among the most loosely packed natural sediments (Kolbuszewski, 1950; Allen 1972). If cohesionless, such deposits are highly susceptible to post-depositional disturbance, liquefaction, and the formation of secondary water-escape structures, especially dish and pillar structures (Lowe and LoPiccolo, 1974; Lowe, 1975). Because of the larger volumes of fluid flushed through higher parts of the beds, dishes tend to be narrower and more strongly concave and pillars more common upward (Lowe, 1975) (Figs. 3B and 8A). This stage of suspension sedimentation probably accounts for the bulk of the high-density suspended load and can form almost instantaneously sand and pebble beds many meters thick that are devoid of traction sedimentation structures.

The ideal sequence of sedimentary divisions deposited by a sandy high-density turbidity current passing through traction, traction carpet, and suspension sedimentation stages is shown in Figure 8. These are here termed the "S" turbidite divisions. The S_1 division shows traction structures, generally plane lamination and cross-stratification reflecting plane beds and dune-like bedforms, respectively. The overlying S_2 division contains thin horizontal layers commonly showing inverse grading and basal shear laminations. These layers are interpreted to represent traction carpet deposits. The uppermost division, S_3, deposited by suspension sedimentation, may be structureless or normally graded and it commonly contains water-escape features. The S_{1-3} sequence reflects a pattern of flow evolution that is mechanically similar to that followed by low-density currents in depositing the T_{bc} (traction structures), T_d (suspension/traction lamination), and T_e (massive suspension deposits) sequence of divisions.

Deposition of the coarse-grained high-density suspended-sediment load leaves a residual current containing in turbulent suspension fine population 1 grains that did not settle with the coarser detritus. These residual currents can range from true low-density flows to those containing relatively high concentrations of fine suspended sediment, and can move and possibly accelerate downslope as discrete turbidity currents similar to those developed

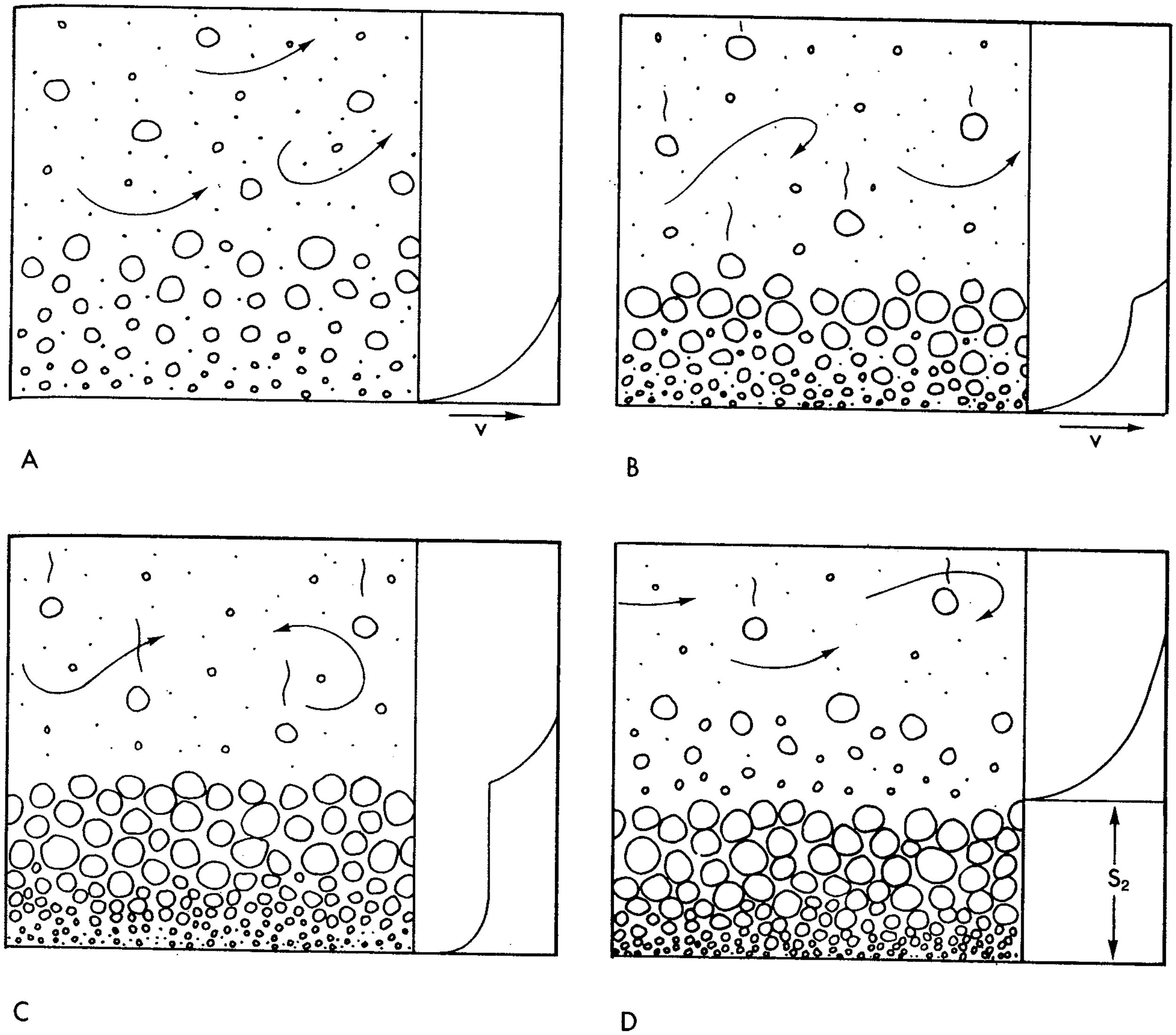

FIG. 7.—Origin of traction carpet layers. A) Basal part of high-density flow shows development of inversely graded zone due to intergranular dispersive pressure. Note generalized velocity profile on right. B) Fallout from suspension increases clast concentration in basal layer and results in formation of traction carpet in which grains are fully supported by dispersive pressure. C) Continued fallout from suspension loads traction carpet and causes freezing and plug information in upper part of traction carpet. D) Final freezing of traction carpet results in formation of new inversely graded basal flow layer above deposit. Process repeats itself.

above cohesive flows (Hampton, 1972). This may represent one of the principal mechanisms by which low density turbidity currents form. Although these residual flows may completely bypass areas of high-density turbidity current deposition, they can have significant local effects. They may shear, liquefy, and homogenize the loosely packed high-density suspension deposits (Middleton, 1967) (Fig. 9A). They can erode or rework the upper parts of S_3 units, leaving relatively thin caps of high-velocity plane laminations or large-scale cross-stratification that are not part of the normal Bouma sequence (Figs. 5b and 9A) (Hiscott and Middleton, 1979). If unsteady, residual low-density currents can deposit sediment above that laid down during the high-density depositional stages (Figs. 8 and 9B). The resulting low-density turbidity current deposits commonly include a high proportion of coarse- to very coarse-grained sand, alternating thin, coarse high-density S_3 and laminated T_b units, and soft-sediment deformation structures (Fig. 9B), features suggesting that the residual currents commonly retain some coarse sediment in suspension and that the change from high- to low-density flows is transitional. Toward their tops, these deposits often include climb-

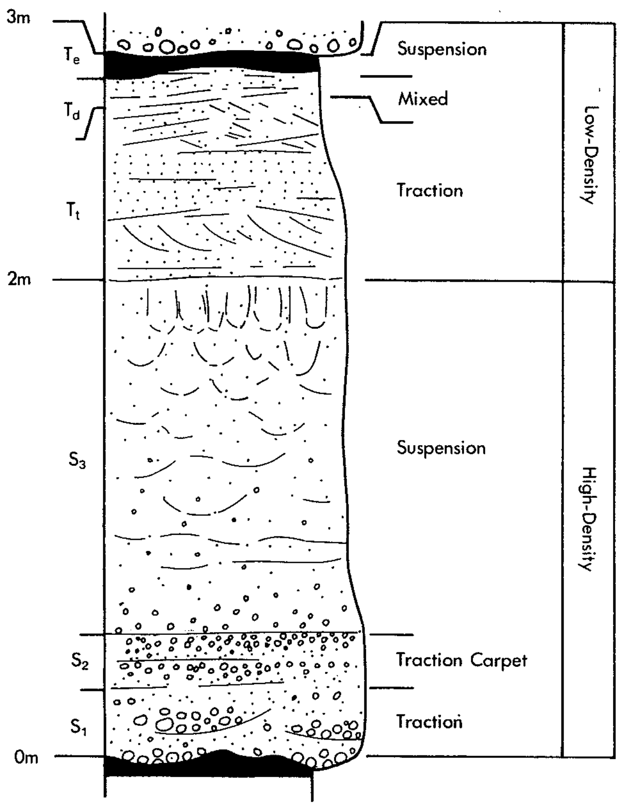

FIG. 8.—Ideal deposit of a sandy high-density turbidity current showing both high-density (S_{1-3}) and late-stage low-density (T_t, T_{d-e}) divisions. T_t commonly includes T_c at the top, underlying layers of flat-lamination (T_b), and large-scale cross-stratification that is not part of the normal Bouma sequence.

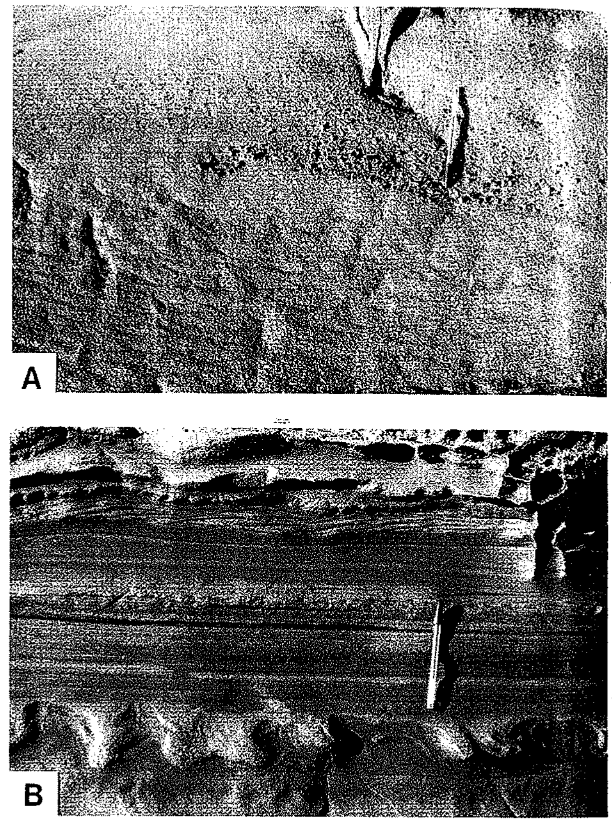

FIG. 9.—A) High-density suspension sedimentation deposit (S_3) showing dish structures increasing in concavity upwards. Along width of outcrop, upper surface of S_3 layer shows regularly repeated wave-like crests, one of which occurs in left-center of picture. Crests appear to represent either Helmholtz waves developed on top of liquefied S_3 division or dunes formed on more coherent bed due to current flow over deposit. Wave-forms show soft-sediment deformation and overturning reflecting flow from left to right, and concentrations of granules on lee-sides. Note sediment homogenization and eradication of dish structures in uppermost portion of suspension deposit, probably as a result of shearing of fluid-like liquefied sediment by the later current. B) Low-density turbidity current divisions capping a thick high-density turbidity current deposit. Alternation of textural and structural divisions suggests that flow was surging during decline. Sandstone layer at base of photo represents top of high-density suspension sedimentation unit (S_3). Overlying layers show convolute lamination, formed by foundering of thin, coarse-grained S_3 division into fine-grained unit; zones of flat lamination (T_b); and climbing-ripple cross-lamination (T_c). Above cross-laminations are two thin graded S_3 divisions succeeded by the base of the next thick, coarse-grained, high-density turbidity current deposit. T_d and T_e divisions are absent.

ing-ripple cross-lamination, indicating continued rapid sediment fallout from suspension, and generally show poorly developed T_d and T_e divisions, reflecting the bypassing of most of the finest material (Fig. 9B). In many cases, because of their high velocities, thickness, and coarse loads, residal low-density currents deposit basal units showing large-scale cross-stratification (Hubert, 1966; Allen, 1970; Cas, 1979; Hiscott and Middleton, 1979).

The complete ideal sedimentation unit deposited during successive high- and low-density stages of deposition by a coarse-grained sandy high-density turbidity current is shown in Figure 8. Many variations in the sequence of divisions are possible. Rapidly decelerating flows may begin deposition either by traction carpet or suspension sedimentation. Modifications of the Bouma sequence proposed by Hubert (1966), Allen (1970), and Cas (1979, Fig. 9) and the proximal sediment gravity flow model of Aalto (1976) represent specific variations on this general sequence of deposition. Fluctuations in the rate of suspended-load fallout may result in traction sedimentation, traction carpet sedimentation, or suspension sedimentation at almost any stage until the high-density turbidity current has declined to a low-density flow.

Considerable variability in the structuring of sandy high-density turbidity current deposits may also result from variations in the mean size of the suspended load. Flows composed largely of fine- and very fine-grained sand will not deposit traction carpet layers because of the negligible dispersive pressure between such fine grains. Also, the low settling velocity of fine sediment might tend to prevent mass-collapse of the suspended load and to prolong the interval of traction sedimentation. A control of grain size on depositional mechanics of high-density flows is suggested by observations of Mutti and Ricci-Lucchi (1975) that, in inner and mid-fan channel facies, medium- to very coarse-grained sandstones (facies A) generally lack internal lamination, except near the tops, whereas beds composed of "medium-coarse to fine sand" characteristically show thick, broadly undulating or flat laminations and sometimes cross-bedding (facies B) (Fig. 5A, T_t division at top of unit).

Sediment Deposition from Gravelly High-Density Turbidity Currents.—The sedimentation history of gravelly high-density turbidity currents can be traced both hypothetically and with reference to observations of natural conglomeratic deposits, especially those of Walker (1975, 1977) and Aalto (1976). Because of the presence of grain populations 1, 2, and 3 above, such flows probably range from dense, gravel-rich dispersions dominated by intergranular dispersive pressure and closely resembling density-modified grain flows (Lowe, 1976a) to more dilute, sandier flows in which turbulence contributes significantly to clast support. Although organized traction-sedimentation bedforms might theoretically be formed and preserved beneath steady or quasi-steady gravelly flows, the inevitable development of dispersive pressure in flows containing concentrated large clasts (Walker, 1965, 1975; Fisher, 1971), the tendency of the largest clasts to concentrate near the flow base (Govier and Aziz, 1972), and observations by Walker (1975, 1977) that traction structures do not characterize the coarser, more proximal submarine-fan conglomerates indicate that such bedforms are rarely developed and preserved. Perhaps large-scale cross-stratification and flat-layering in coarse deep-water conglomerates in Chile (Winn and Dott, 1977) could reflect traction sedimentation beneath gravelly high-density flows.

Most very coarse gravel is probably transported near the bed within a highly concentrated traction carpet (Walker, 1975, 1977; Aalto, 1976) and in suspension in the lower part of the turbulent flow. Depositon of the gravel will occur nearly instantaneously once flow velocity drops below that necessary to maintain the dispersive pressure in the traction carpet and involves freezing of the traction carpet and direct suspension sedimentation of coarser suspended gravel (Walker, 1975, 1977). Hence, the deposit generally includes a basal inversely graded traction carpet layer (Fig. 3C) overlain by a normally graded suspenson sedimentation unit. This sequence coincides with the inversely to normally graded conglomerate facies of Walker (1975, 1977) and with the basal conglomeratic layers I, II, and III of Aalto (1976). Further downslope, toward the distal end of the gravel sedimentation wave, extreme flow unsteadiness results in direct suspension sedimentation of gravel without traction carpet development. The deposit consists of a basal normally graded gravel layer representing the graded conglomerate facies of Walker (1977). Deposition of the bulk of the gravel-sized material leaves a relatively steady sandy high-density turbidity current that may rework the upper layers of the underlying suspension-sedimentation deposit, forming the graded-stratified conglomerate facies of Walker (1975, 1977) or layer IV of Aalto (1976).

The residual high-density sandy turbidity current, transporting small pebble- through clay-sized debris, may continue downslope as a relatively steady flow or begin to deposit immediately due to continued deceleration. It is important to note, however, that deposition of population 2 grains often occurs independently of that of population 3 because sand-sized grains are supported by flow turbulence and hindered settling, not dispersive pressure. Much sand completely bypasses areas of gravel deposition. Consequently, individual turbidites including both coarse gravel and sand stages of high-density deposition are uncommon, most deposits showing major downslope facies changes and a strong lateral separation of sand and gravel (Fig. 10). Following deposition of the coarser gravel, the sedimentation history is that of a sandy high-density turbidity current. An ideal deposit formed by separate waves of high-density gravel and sand deposition is shown in Figure 11A and is very sim-

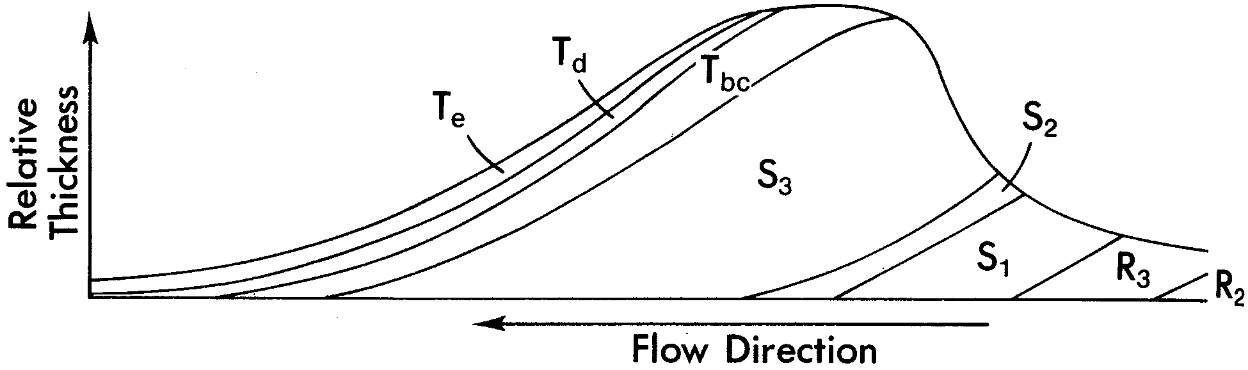

FIG. 10.—Generalized diagram showing downslope changes in turbidite organization. Horizontal line represents base of turbidite. A vertical line drawn through each point on horizontal line shows arrangement and extremely schematic thickness relationships of high- and low-density divisions deposited at that point by turbidity current.

ilar to the "coarse, proximal-exotic sediment gravity-flow" model of Aalto (1976, Fig. 2, p. 916).

The individual structural divisions formed by the gravel wave of deposition are here designated R_1 (coarse gravel showing traction structures), R_2 (inversely graded gravel layer), and R_3 (normally graded gravel layer).

Surging Flows.—Surging undoubtedly characterizes many sediment flows. Instead of showing a continuous decrease in velocity, competence, and capacity, surging flows show an oscillating decline, each surge characterized by an abrupt velocity increase followed by a gradual deceleration. In general, each surge exhibits lower maximum and minimum velocities than the ones preceeding it. The resulting deposits are likely to contain corresponding repetitions of grading and structure divisions (Figs. 9B and 11B).

Downslope Changes.—Inferred downslope changes in the sequence of divisions in high-density turbidity current deposits reflect downslope flow evolution and tend to parallel those in low-density flow deposits (Figs. 10 and 12). In "proximal" environments within submarine canyons and inner fan channels, high-density turbidity current deposits will consist either of coarse gravel showing R_2 and R_3 divisions or of sand and fine gravel arranged in complex S_{1-3} cycles. Individual divisions may be missing within any one turbidite, most commonly S_1 and S_3 because of extreme flow unsteadiness. At its extreme distal extent, a high-density current deposits only a thin S_3 division. Where overlain directly by divisions of traction structures deposited by the decelerating residual low-density flow, this S_3 division is the same as T_a (Figs. 10 and 12). The resulting $S_3 = T_a, T_{b-e}$ succession represents the classical turbidite sequence (Bouma, 1962).

Liquefied and Fluidized Flows

Liquefied flows can be initiated either by slumping followed by liquefaction of the failed sediment or by spontaneous liquefaction (Terzaghi, 1947) on slopes exceeding 3° or 4° (Lowe, 1976b). Moving downslope, they may either deposit sediment directly as laminar suspensions or accelerate, become turbulent, and evolve into high-density turbidity currents (Inman, 1963; Chamberlain, 1964; van der Knapp and Eijpe, 1968; Lowe, 1976b).

Simple direct deposition from a liquefied flow should produce a deposit like that formed by setting of a laminar high-density suspension (Figs. 3B and 9A). The deposit will be grain-supported, consist largely of fine-grained sand and coarse silt (Lowe, 1976b), and may be massive or show water-escape structures (Fig. 12, models 12 and 13). It may be ungraded partially graded, or normally graded over its entire thickness. Where present, grading will be coarse-tail grading.

Successive failures along a single scarp commonly produce retrogressive flows, and the resulting deposits may show a series of water-escape events reflecting several surges of deposition (Lowe, 1976b). The ambient water above liquefied flows may be set into motion by shear at the flow surface. These aqueous currents may persist after deposition of the liquefied debris and rework the tops of

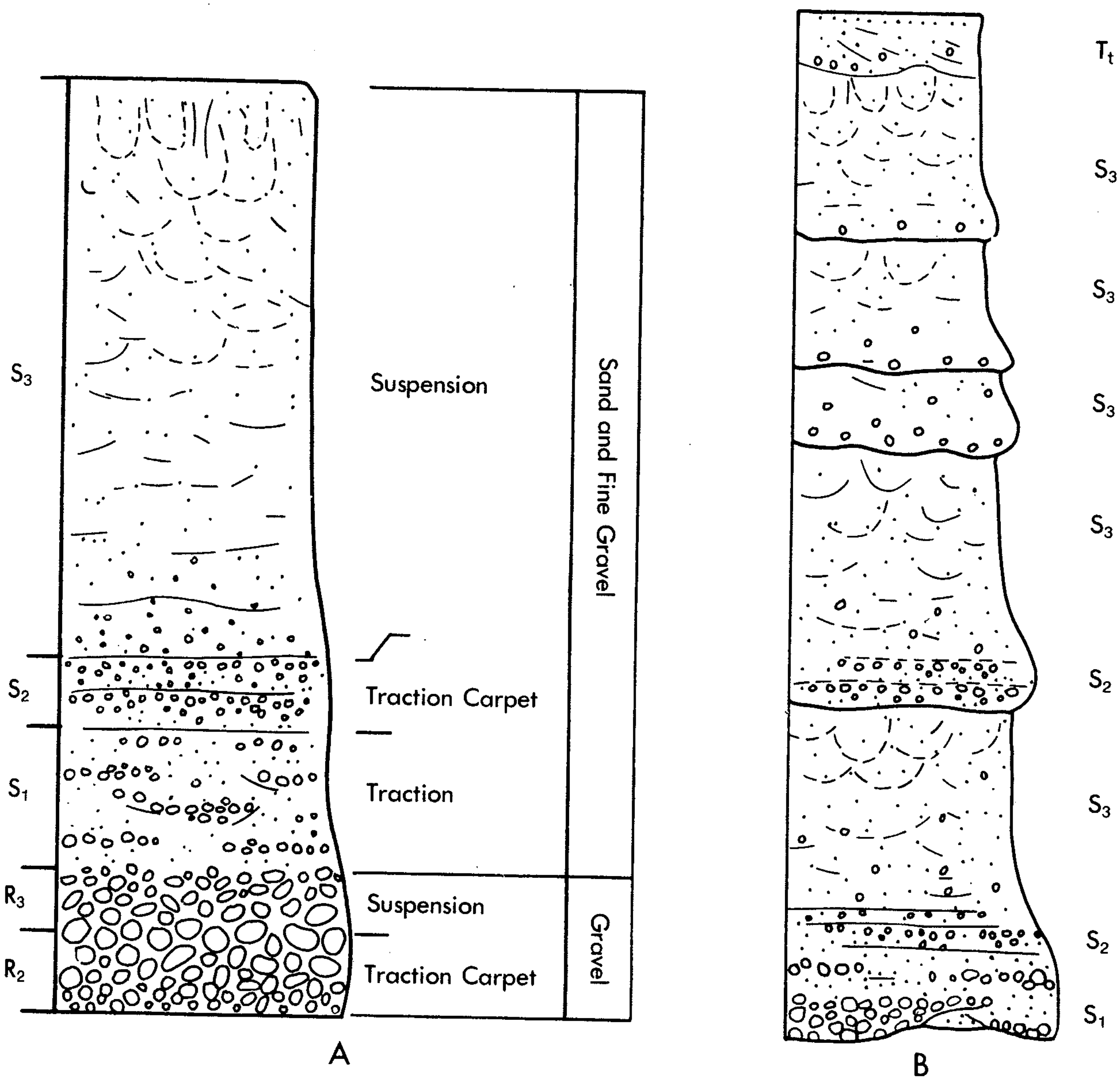

FIG. 11.—A) Ideal sequence of divisions deposited by a single high-density turbidity current declining through discrete gravelly and sandy sedimentation waves. Because of downslope separation of gravel and sand depositional stages, complete high-density sedimentation units such as this are rarely formed. B) Complex sedimentation unit deposited by surging sandy high-density turbidity current.

the liquefied flow deposits, forming thin caps of sand showing traction structures.

Because of the laminar character and high-density of liquefied flows, their deposits will tend to show flat, unscoured bases.

Fluidized flows either decelerate and become liquefied flows or accelerate and become turbidity currents, and their deposition need not be treated separately.

Grain Flows

True grain flows are dispersions of rigid particles maintained against gravity solely by dispersive pressure arising from grain collisions. Middleton and Hampton (1973, 1976) and Lowe (1976a) have reasoned that steady grain flows of sand-sized particles can exist only on slopes approaching the static angle of repose, generally between 18° and 28° for subaqueous sands. Lowe (1976a) has further suggested that individual grains flows of sand, in the absence of modifying influences such as a more rapidly moving overlying current or a high-density interstitial matrix, will generally be less than 5 cm thick because of the inability of grains at the base of the flow to produce

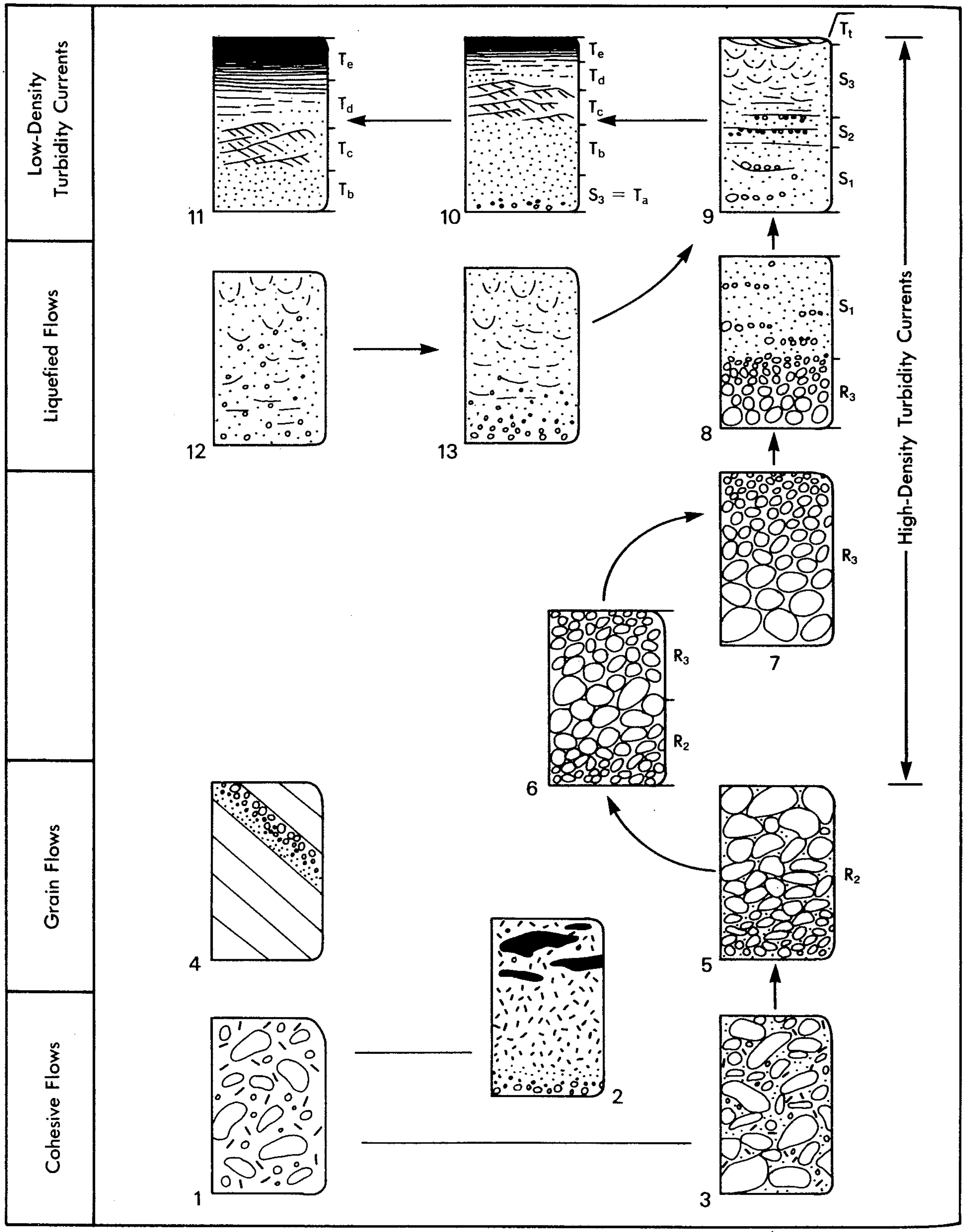

FIG. 12.—Summary of the main deposit types formed during deposition from sediment gravity flows. Lines without arrows (i.e., 1–2 and 1–3) connect members between which there probably exists a continuous spectrum of flow and deposit types but which are not parts of an evolutionary trend of single flows. Arrows connect members which may be parts of an evolutionary continuum for individual flows. The transition from disorganized cohesive flows (1 and 3) to thick, inversely graded density-modified grain flows and traction carpets (5) and to turbulent gravelly high-density turbidity currents (6) is speculative but may occur.

dispersive pressure sufficient to support against gravity a thick overlying column of dispersed sediment.

Deposition from grain flows is by frictional freezing. The deposits of sandy flows consist of grain-supported sand in individual flow units that are thin, commonly inversely graded, and inclined at the angle of repose (Fig. 12, model 4). Such sedimentation units are most commonly developed as individual avalanche foreset deposits on subaerial and subaqueous dune slipfaces.

Two other types of grain dispersions are important in the formation of natural deposits: those involving sediment mixtures, and traction carpets formed beneath and driven by overlying flows. The latter have already been described in some detail. In the former, discussed by Middleton (1970), Middleton and Hampton (1976), Rodine and Johnson (1976), Hampton (1979), Mullins and Van Buren (1979), and Lowe (1976a, 1979b), much of the excess mass of larger particles is supported by the buoyant lift of a dense sediment-water matrix. The matrix mixtures can vary from essentially cohesionless silt-sand suspensions between gravel-sized clasts (Lowe, 1976a) to cohesive clay-silt-sand-gravel slurries (see e.g., Rodine and Johnson, 1976).

Cohesionless flows of this type have been termed density-modified grain flows (Lowe, 1976a), and deposits which probably represent such flows have been described from the Mesozoic Great Valley Sequence of western California (Mansfield, 1972; Lowe, 1976a) and from other areas (Fisher and Mattinson, 1968; Walker, 1975, 1977). Individual sedimentation units generally exceed 0.4 m in thickness and consist of clast-supported pebbles and cobbles set in a poorly sorted sand, silt, and clay matrix (Figs. 3C and 12, model 5). Inverse grading is common in cobble beds, reflecting the relatively high dispersive pressure between large clasts, but pebbly beds tend to be ungraded or to show poorly developed inverse grading, suggesting relatively low dispersive pressure and little size-sorting capability (Lowe, 1976a). Should such flows become turbulent, tending to evolve toward turbulent high-density turbidity currents, some normal grading might be present.

Cohesive Debris Flows

Cohesive debris flows (Lowe, 1979b) or mudflows, also termed "true debris flows" (Middleton and Hampton, 1973, 1976), are distinguished from grain flows in that the larger particles are supported by the cohesiveness of a sediment-water matrix rather than by dispersive pressure among rigid grains. Cohesive debris flows have been shown to be effective transporting agents in both subaerial and subaqueous environments. The properties and evolution of cohesive flows have been studied by Johnson (1965, 1970), Johnson and Hampton (1969), Rodine and Johnson (1976), and Hampton (1972, 1975, 1979).

Flows that deposit sediment by cohesive freezing encompass a broad spectrum of rheological behavior and sediment-fluid mixtures. Cohesive debris flows or "true debris flows" represent one end member in which the larger clasts are actually supported by the buoyancy and cohesiveness of the clay-water matrix. Their deposits, which include many so-called pebbly mudstones, boulder clays, tilloids, and diamictites, consist of pebble-, cobble-, and sometimes boulder-sized clasts suspended in a clay-silt-sand matrix (Figs. 3D and 13A). Many such deposits show an upper size limit to the matrix-supported particles suggesting that larger blocks, if originally present, were able to settle through the matrix during flowage (Sharp and Nobles, 1953; Lowe, 1979b). The remaining clasts are commonly uniformly dispersed within the matrix reflecting the existence of weak, intergranular dispersive pressure (Lowe, 1976a, 1979b) or flow turbulence (Enos, 1977) (Fig. 13A).

In many cohesive flows, the largest clasts are not actually suspended within the mud-water matrix but remain more or less in contact with one another while rolling, sliding, and intermittently bouncing downslope. Flows described by Bagnold (1954), Curry (1966), Lowe (1979b), Sharp and Nobles (1953), and many others appear to be of this type. The clay-water matrix, although making up as little as 5 percent of the flow by volume, provides buoyant lift, reducing the effective weight of the clasts, and lubricates the grains, preventing frictional locking (Rodine and Johnson, 1976). The deposits of such flows show largely clast-supported fabrics and include a variable, but sometimes small, proportion of clay (Fig. 13B) (Curry, 1966; Lewis, 1976; Rodine and Johnson, 1976; Winn and Dott, 1977).

Enos (1977) has suggested that many cohesive flows are turbulent at some stage in their evolution. Fully turbulent flows might suspend

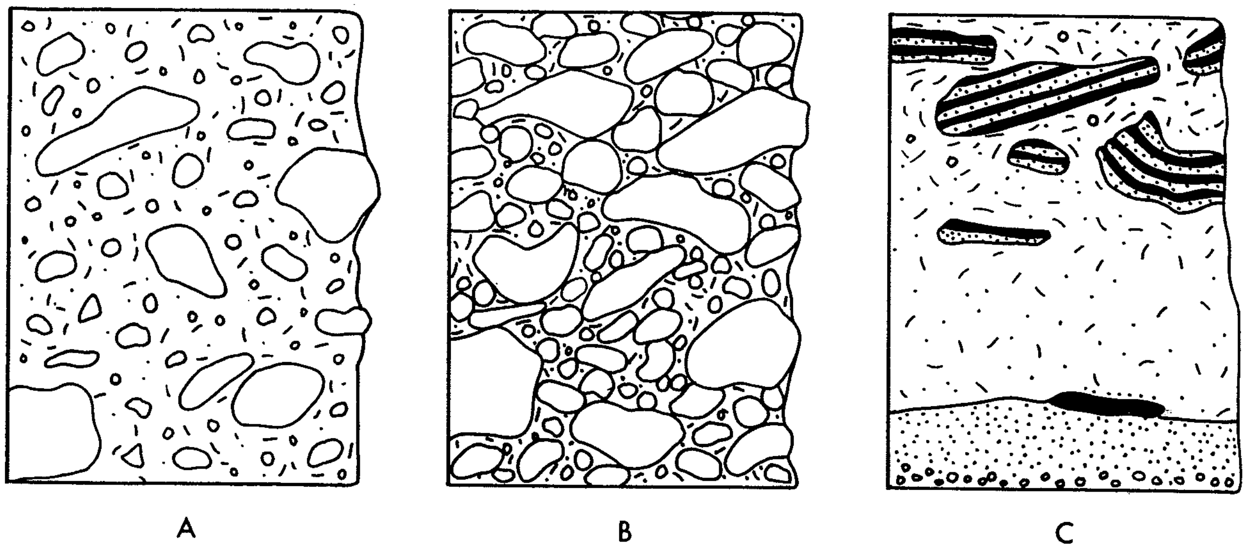

FIG. 13.—Cohesive flow deposits. A) Massive, structureless, matrix-supported pebbly mudstone deposited by cohesive flow in which clasts were actually suspended in and supported by the matrix. B) Massive, structureless, clast-supported muddy conglomerate deposited by a flow in which the clasts were lubricated but not fully supported by or suspended within the matrix. C) Stratified deposit formed by suspension sedimentation of coarser quartz-density sand and gravel from the lower part of a turbulent cohesive flow followed by cohesive freezing of the upper part. The top of the flow deposit, from which the larger quartz-density grains have not settled, may have already been a rigid plug during accumulation of the basal suspension layer. Mount Rogers Formation (upper Precambrian), Virginia.

clasts larger than those that could be supported by matrix cohesiveness and buoyancy alone. During deceleration, initial deposition occurs through damping of turbulence and direct suspension sedimentation of the coarsest part of the suspended load. The final phase of deposition involves freezing of the remaining laminar flow. The resulting deposit consists of a basal layer, possibly graded, of structureless grain-supported sediment deposited by suspension sedimentation capped by a matrix-supported freeze unit. Deposits of this type have been identified by the author from upper Precambrian strata in the Southern Appalachian Mountains (Fig. 13C) and have been described by Marschalko (1970) and Winn and Dott (1977). Because deposition occurs mainly during the final stages of movement, it takes place largely under conditions of laminar flowage. The deposits may closely resemble those of liquefied flows (Lowe, 1976b, Fig. 4), and it seems likely that there is a continuous flow spectrum between cohesionless liquefied and cohesive debris flow.

CONCLUSIONS

Figure 12 summarizes the proposed models of sediment gravity flow deposits. Particularly important in understanding the observed complexity of "proximal" submarine canyon and fan channel conglomerate and sandstone facies is the evolutionary spectrum of flow types from high-density to low-density turbidity currents (models 5 through 11, Fig. 12). The sedimentological distinction between these flow types has been discussed in terms of the influence of particle concentration on grain support and deposition. In high-denity flows of sediment coarser than about medium-grained sand, particle suspension is dependent on concentration effects, whereas in low-density flows the grains are supported individually by turbulence alone. Although discrete high- and low-density flows may exist, it has been inferred that individual flows commonly evolve from the former to the latter through deposition of highly concentrated coarse-grained suspended-sediment clouds. Also, many turbulent suspensions, particularly those transporting coarse-grained sediment, show much greater grain concentrations toward their bases than near their tops (Smith, 1955; Sinclair, 1962; Newitt, Richardson and Shook, 1962). The lower parts of such flows may behave as high-density suspensions whereas the tops are low-density in character (Walker, 1965, 1978).

The structuring of natural sediment-flow deposits and the inferred depositional mechanics of concentrated suspensions suggest that high-density turbidity currents transporting a wide size-range of detritus can deposit sediment through a series of discrete sedimentation waves. The first wave commonly involves deposition of the coarsest gravel by traction carpet and suspension sedimentation to form inversely graded (R_2) and massive and normally graded (R_3) gravel divisions, respectively. Deposition of the finer gravel and sand from the residual sandy high-density turbidity current occurs during a second wave by traction sedimentation beneath the nearly steady high-density flow (S_1) followed, as unsteadiness and suspended load fallout increase, by intervals of traction carpet (S_2) and suspension sedimentation (S_3). The residual low-density current continues downslope, eventually depositing its sediment load during a third sedimentation wave to form the Bouma divisions, T_{b-e}.

Liquefied flow deposits (models 12 and 13, Fig. 12) can closely resemble the S_3 divisions of turbidites, but, because liquefied flows do not readily transport coarse sediment for long distances, will generally consist of fine-grained sand to coarse silt. They will also not be part of a regular sequence of structures including other divisions such a S_1 and S_2.

Grain-flow deposits of sand are restricted to thin avalanche units on angle-of-repose slipfaces (model 4, Fig. 12), but gravelly flows and density-modified grain flows may deposit thicker layers (model 5, Fig. 12). These coarse-grained flows may be effective in transporting sediment in submarine canyons and channels primarily when they occur as traction carpets driven in part by overlying turbulent flows.

Debris flows dominated by the presence of a dense cohesive interstitial matrix range from those in which large blocks are fully suspended in the matrix to those clast-rich varieties in which the matrix essentially serves as a pore-filling lubricant. The deposits may thus range from fully matrix-supported (model 1, Fig. 12) to fully clast-supported (model 3, Fig. 12) and from massive, where there is no tendency for the clasts to be size-segregated, to stratified or normally graded (model 2, Fig. 12), where matrix strength is insufficient to fully support the clasts against gravity allowing differential settling during deposition.

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