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Mass-emplaced sand-fingers at Mararoa construction site, southern New Zealand

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ABSTRACT

During work on a dam construction site in South Island, New Zealand, outflowing ground water resulted in extensive local mass-transport of the sands being excavated. A series of small scale sand fans was built up, probably mainly by laminar mass-flow processes. The surfaces of the fans were made up of a series of complexly interdigitating sand-fingers that are inferred to have been emplaced by viscous plug-flow. Other sedimentary processes associated with the building and synsedimentary destruction of the fans included rapid grain-flow, liquefaction and progressive slumping. Although small in scale, the Mararoa mass-flow fans may be a close analogue for some of the many 'fluxoturbidite' or 'proximal flysch' facies described in the sedimentological literature, and their geologic implications are therefore briefly discussed.

INTRODUCTION

The last few years have seen some major advances in our understanding of the rheological behaviour of various types of mass transport (Johnson & Hampton, 1969; Johnson, 1970). Together with recent field observations by a number of workers (e.g. Stauffer, 1967; Fisher, 1971; Hendry, 1973), these experiments have given us a much firmer basis from which to attempt the interpretation of fossil sediments emplaced by mass-flow. However, apart from the critically important accounts of subaqueous transport processes acting in the heads of the Californian submarine canyons (summarized by Shepard & Dill, 1966), and the eye-witness reports of Recent subaerial debris-flows in Johnson (1970), there are few recent descriptions of naturally occurring mass-flows that bear significantly on the problems of recognizing mass-transported sediments in fossil situations. This note describes and illustrates some small-scale mass-transport structures produced in remobilized Quaternary sands in southern New Zealand. The necessarily transient nature of construction site excavations unfortunately allowed only brief observations to be made, as the features described below were destroyed within 36 h of their being located.

GEOGRAPHIC AND GEOLOGIC SETTING

The sedimentary phenomena described below occurred in January, 1974, on the New Zealand Ministry of Works dam construction site at the confluence of the Mararoa and Waiau Rivers, near Te Anau. The damsite is situated in a geologically complex area that is widely covered by Quaternary deposits (Wood, 1966, 1969). The major lithologies in the dam abutments are moraines and alluvial terrace gravels (McKellar, 1973), while the control structure itself is in an area of deformed glacio-lacustrine silts with minor tillites. Excavations with a Koering digger in the upstream channel (Fig. 1) passed into an unconsolidated sand that overlies the lacustrine silts of the control structure area. It is this sand that was involved in the mass-flows described below.

Fig. 1. View north across the Mararoa damsite upstream channel. Trench excavated in unconsolidated sands by Koering digger. Note perched water table about 1 m above floor of trench, with continuous fan-bench developed below this level. Main stream of muddy water in bottom of trench flows towards camera.

LITHOLOGY INVOLVED IN MASS-FLOW

The major lithology involved in the mass-flows is an unconsolidated, well-sorted, brown, fine-medium, lithic quartz sand, with conspicuous cross-bedding (sets 5–15 cm high) in outcrop. The sedimentary structures, mineralogy and general field appearance of the sand are closely similar to those of the Manapouri Sand, a late Quaternary formation mapped by McKellar (1973) with type locality some 12 km north-west of

the Mararoa damsite. Grainsize analyses were performed by routine wet-sieving (Fig. 2), and reveal the sand as well sorted, with only a little coarse silt and trace amounts of fine silt or clay. The field and laboratory data combine to suggest that the sand represents the beach facies of a glacial lake, like the probably equivalent Manapouri Sand Formation.

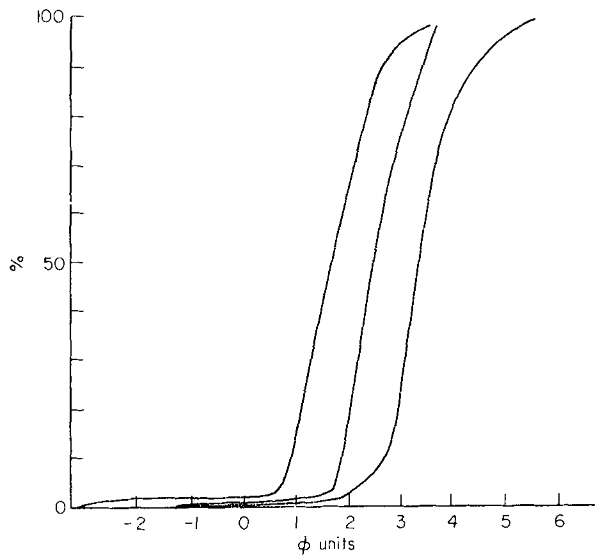

Fig. 2. Grainsize analyses of three sand samples collected from the sand-finger fans illustrated in Fig. 4 (analyses by wet sieving, courtesy New Zealand Ministry of Works, Mararoa Site Laboratory).

CAUSE AND NATURE OF THE MASS-FLOW AND ITS PRODUCTS

(1) Sedimentary mechanisms seen

Preliminary excavation of the upstream channel at Mararoa damsite entailed construction of a trench about 4 m deep. As excavation passed from Damsite Formation silts (McKellar, 1973) into the area underlain by sand, a perched water table became apparent between 1 and 2 m above the floor of the trench (Figs 1, 3) and excavation proceeded in such a way that a continuously sloping trench side was left with water seeping out at the lower levels. The escaping groundwater rapidly smoothed the lower parts of the trench wall, leaving a continuous fan-bench along the side of the ditch, with an approximate slope of 30–40° (Fig. 3). This fan-bench was the site of continuing mass transport of material down to the stream of muddy water in the floor of the main trench. Small sand-flows that developed from the head of the fan-bench, generally on a scale 1–3 cm wide and less than 1 cm deep, were apparently directly fluidized by the escaping groundwater, while at lower levels on the bench similarly sized retrogressively propagating flow-slides (Andresen & Bjerrum, 1967) were apparently generated by spontaneous liquefaction. Velocities, estimated crudely

Fig. 3. Closer view of part of the fan-bench of Fig. 1. Continuous grain-flow, traction and suspension transport of sand taking place down the bench. Note steep, undercut banks above.

by timing small pieces of paper rafted in the flows, were up to 70 cm/s in fast fluid sand-flows, whilst the heads of retrogressive flow-slides propagated back up-slope at speeds generally between 1 and 3 cm/s.

As the steep upper wall of the trench was progressively undercut by the flows, pieces of dry sand crumbled and slumped onto the water-saturated fan-bench, down which they were slowly rafted by the underlying mass-flows. Individual blocks of sand up to several centimetres across occasionally retained their integrity for the whole journey down the fan-bench, but more usually the blocks slowly crumbled and dissolved into the carrier flows, often causing the flow to slacken in speed while it digested the material being incorporated through its upper surface. Eventually, mass-flow processes slackened somewhat, though by no means ceased, and the water issuing out along the top of the fan-bench then moved much material down the bench by conventional traction and suspension processes, producing a typical anastomosing braided-river pattern on the surface of the fan-bench (Fig. 3).

(2) Sedimentary mechanisms inferred

At intervals along the side of the trench, constructional fans could be seen to have built out over the continuous fan-bench (Fig. 4). Such constructional fans were of the order of 5 m wide and 1–2 m high, and carried on their surfaces a series of remarkable sand-fingers similar to those figured as debris-flows by Johnson (1970; Fig. 12.4). The slope of the surface of the sand-finger fans was appreciably less than that of the continuous fan-bench, ranging from 10 to 25° and steepening towards the fan apex.

The sand-fingers were generally between 1 and 10 cm wide and up to a few centimetres long; smaller fingers were only a few millimetres thick but most were between

Fig. 4. Oblique view of a typical sand-finger fan, itself incised and cliffed by later traction cut channels. Note the presence of three morphologically distinct types of sand-finger: (1) large and bulbous (centre right), (2) small and complexly interdigitating (centre), and (3) flat and sub-linear (bottom right and centre left). Horizontal pencil (right centre), 15 cm long.

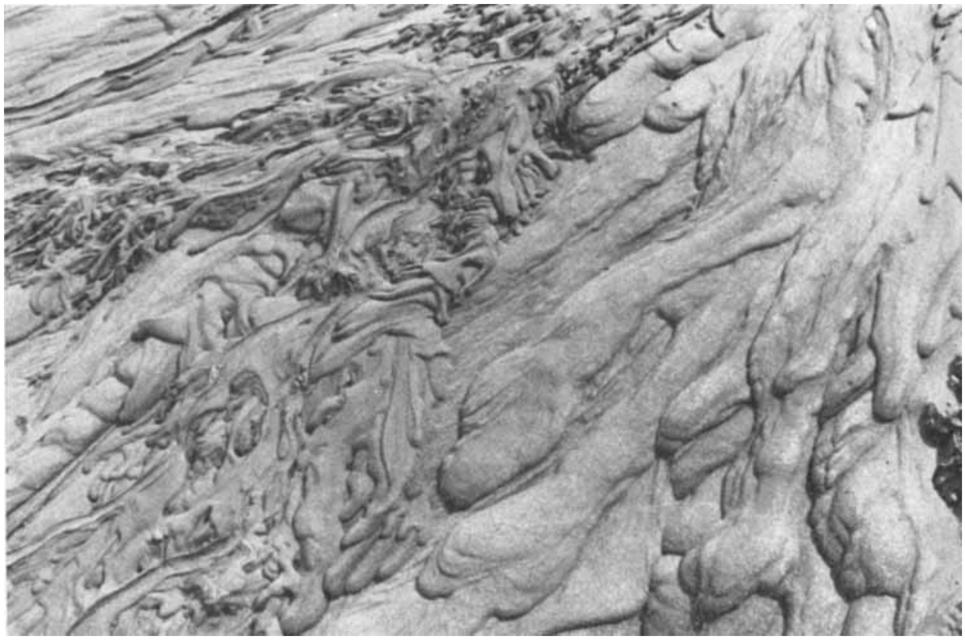

Fig. 5. Close up view of sand-fingers types (1) and (2) of Fig. 4.

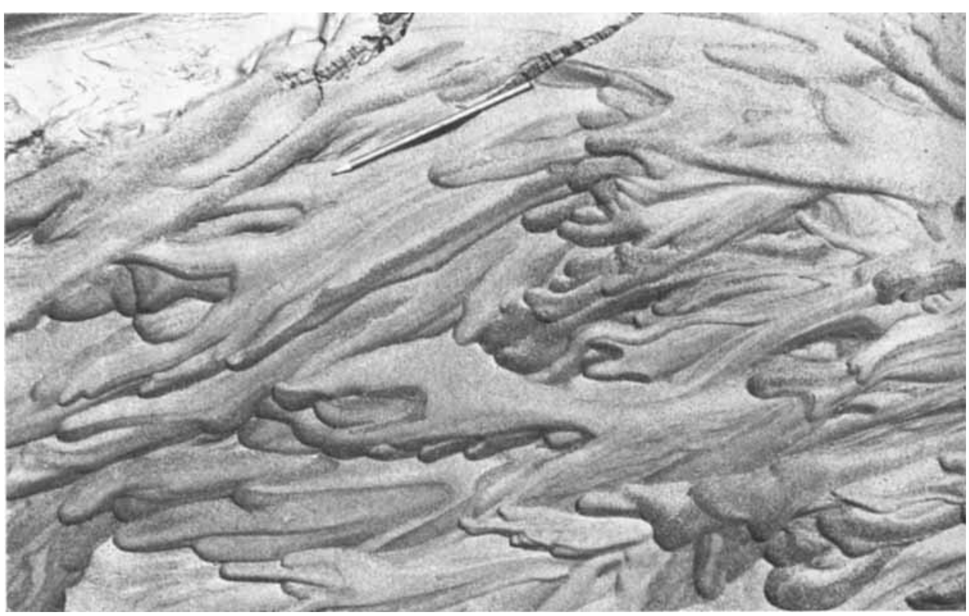

Fig. 6. View of sand-fingers type (3) (pencil 15 cm long). Note sorting of micaceous and mafic components around front and sides of fingers.

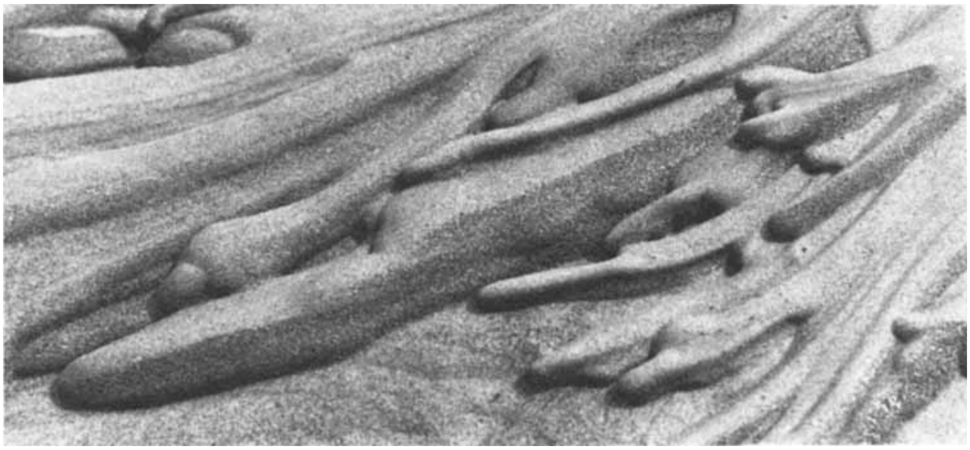

Fig. 7. Low angle oblique view of sand-fingers intermediate between types (2) and (3). Dimensions of major finger crossing picture towards bottom left about 15 cm long, 2 cm wide and 1 cm high.

$\frac{1}{2}$ and 2 cm thick (Figs 5–7). Fingers were convex upwards in transverse profile, and possessed a sharply rounded snout at the front similar to that documented by Johnson for sand-flows generated in laboratory experiments (1970, p. 445 *et seq.*). Some differential sorting had taken place during transport, and micas and other heavy minerals were concentrated around the front and sides of individual sand-fingers (Fig. 7). However, this sorting does not persist with depth, and cross-sections through the fingers revealed massive, apparently unbedded and ungraded sand.

The sand-fingers were presumably emplaced by some type of mass-flow, with closely successive flows resulting in the build up of the complexly interdigitating patterns seen on the fan surfaces. The larger, more globose fingers (Fig. 5) are strikingly similar to inverted flute marks. They were probably emplaced as slow pasty flows, and their somewhat irregularly bulbous (thick) form contrasts with the thinner more regular form of the fingers inferred to have been emplaced from more fluid flows (Fig. 6). Three different morphological types of finger flow could be recognized (Figs 5–7) but it is probable that a larger sample would reveal all intermediates between these types, which presumably only reflect the differing physical properties of the flows that emplaced them. Several different sand-fingers can often be seen to have resulted from a single flow, since they coalesce as traced back towards the fan apex (Fig. 6). Though the formation of well-moulded sand-fingers was not directly observed, speeds of movement of less than 1 cm/s typified slow sand-flows seen to originate adjacent to the Koering bucket as it dug into the sand, and a similar speed of emplacement seems likely for the pastier sand-fingers.

The fans on which the sand-fingers occur represent the latest constructional stage of mass-flow along the trench. Their position, and the presence of a small relict 'stack' that probably marks an earlier stage when the surface on which it rests was a braided part of the continuous fan-bench along the trench sides (Fig. 4, dark spot, left centre), suggests that the sand-finger fans built out onto and over the continuous fan bench. The apices are situated where gullying has cut back deeply into the trench walls to points where sources of pasty sand-flows were available.

The fans themselves are sometimes incised by later erosional channels carrying muddy water, and their extremities may be 'cliffed' by the braided-stream 'flood-plain' produced by such streams and by the main stream down the centre of the trench floor (Fig. 4). Further, individual fingers on the fan may have a shallow gutter channelling into their upper surface (for example, Fig. 5, left-hand side; cf. also Johnson, 1970, Fig. 12.4), perhaps produced by water draining from a later-emplaced sand-finger that had just ceased movement further up slope. However, in other cases such a gutter can be seen to erosionally cross a considerable length of fan surface, and to lead down-slope to the apex of small 'parasitic' fans on the surface or around the edge of the main fan (Fig. 4, centre). In these cases the gutters have clearly served as the conduits through which flows travelled to build up the small fans at their lower ends. Such gutters correspond closely to those already described by Johnson (1970) as typical of mass-transport on several different scales, particularly in their U-profiles and irregular and short overbank fingers, and it seems likely that the major fans were built as a complex series of overlapping and interdigitating smaller fans fed by gutters of this nature.

RELATIONSHIPS BETWEEN SEDIMENTARY MECHANISMS

The most striking aspect of the sedimentary processes seen at the Mararoa damsite was a close relationship, or even gradation, between the various mass-transport phenomena. For example, retrogressively propagating sand-flows proceeded by successive failure in their headward portions (cf. Andresen & Bjerrum, 1967), and this failure involved semi-continuous slumping or sliding as well as apparent spontaneous liquefaction. All gradations between the two phenomena exist, and when such a sand-flow had eaten its way back to the head of the fan-bench it was indistinguishable from the directly fluidized sand-flows that issued at the same level nearby. As Hendry has remarked (1973, p. 133), the distinction between fluidization and liquefaction (cf. Middleton, 1970) may be more formal than real in any realistic sedimentary situation.

A further example of a close relationship between slumping and liquefaction was observed on some of the fans, and suggests that at least some of the mass-deposited sediment in these fans was deposited in metastable equilibrium. When the more distal portions of these fans were walked over, the sand directly liquefied underfoot, presumably due to increased normal pressure. Liquefaction started in discrete footprint areas, but these soon coalesced into a single pool of liquefied sand which propagated headwards for short distances due to rotational slumping higher on the fan (Fig. 8). Individual slump blocks slowly detached from the head walls of the liquefied area, and then melted into the surrounding pool of liquefied sand.

The general conclusion seems clear, that although we may find it formally useful to isolate certain aspects of mass-transport and treat them as discrete phenomena, virtually the whole range of phenomena are likely to be involved at one stage or another in any dynamic sedimentary mass-transport situation. Disentangling the depositional details of sedimentary beds in proximal mass-transport facies will therefore never be easy, and often impossible.

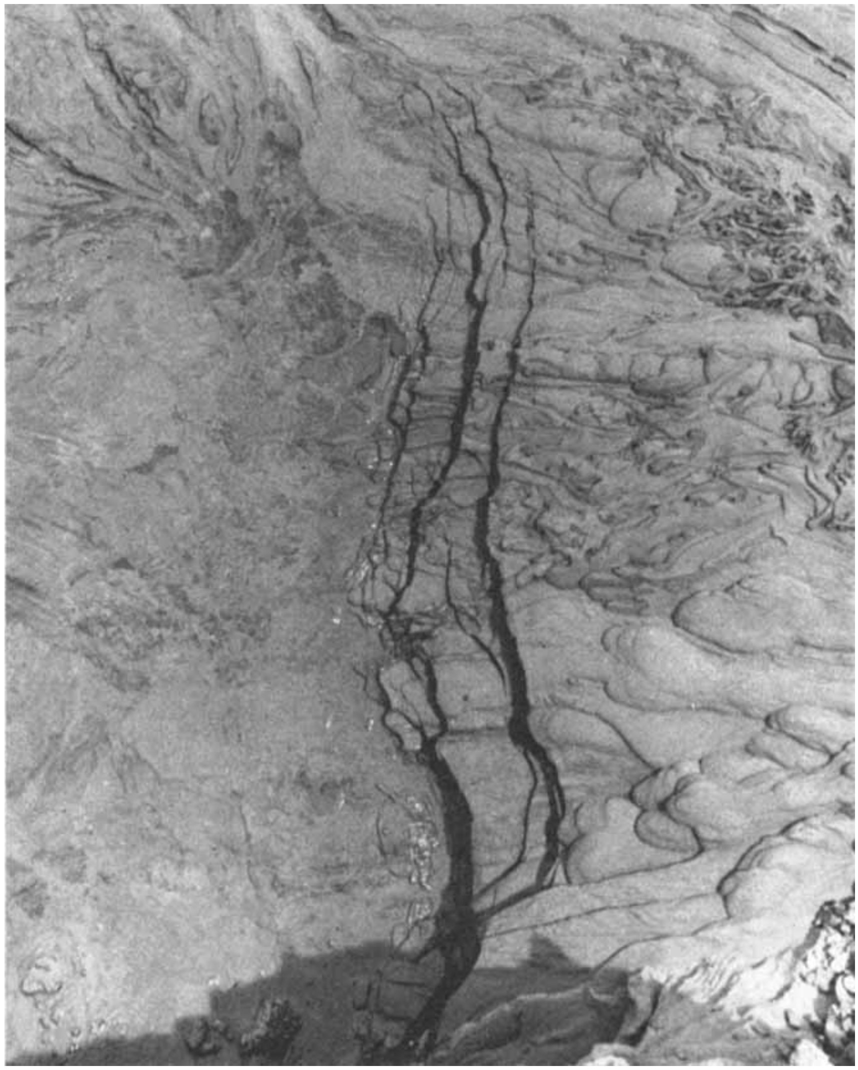

Fig. 8. Oblique vertical view of the same fan as **Fig.** 4, after walking across its distal slopes had caused liquefaction. Note the headward propagation (to the right) of the liquefied area.

THE NATURE OF TRANSPORT

In all cases of grain-flow that were closely examined, flow was clearly of a laminar nature (cf. Johnson, 1970, p. 442), contrasting strongly with the turbulent nature of transport in the adjacent muddy streams of groundwater. Furthermore, for the higher velocity fluidized and retrogressive sand-flows, flow appeared to be of plug-flow type (Johnson, 1970, p. 495 *et seq.*); that is, shear was concentrated along the sides (and presumably around the bottom) of the flow with the centre being rafted along as an essentially undisturbed plug. This was particularly clearly seen when homogeneous

pieces of dry sand fell from above into moving grain flows, since some of these extremely poorly consolidated lumps of sand were gently transported distances of several metres without being dissolved into the flow.

The close relationship between the morphology of the sand-fingers and similar deposits produced from laboratory slurry-flows (Johnson, 1970), particularly the sorting of heavier and micaceous components around the edges of the flow and the shape and height of the snout, suggest that plug-flow typified the emplacement of the sand-fingers also. However, the grain-size analyses (Fig. 2) demonstrate the virtual absence of mud from the Mararoa sand-flows (Johnson's laboratory flows mostly contained appreciable mud), and it is therefore likely that transport was by true inertial grain-flow (cf. Bagnold, 1954) rather than by slurry-flow in the strict sense. (The term 'slurry-flow' is used here as descriptive of mass-flows where the continuous phase is a mud-water slurry rather than plain water; such flows generally generate a dispersive pressure in the viscous region of Bagnold (1954). Johnson & Hampton (1969) have demonstrated experimentally that as little as 10% mud will suffice to move flow into the viscous region.)

In areas further along the main trench at Mararoa, occurrences of dry sand displayed a range of grain-flow phenomena similar to those already described, particularly retrogressive flow sliding and slumping. Vertical outcrops of such dry sand accumulated a fan-bench at their foot, similar to the water-saturated example already described though slightly steeper in slope (see also Fig. 5 in McKellar, 1973). Though the more bulbous types of sand-finger were absent, the surfaces of these dry-sand fans nonetheless preserve individual flows as flattened 'fingers' analogous to those seen on their water-saturated counterparts (cf. Fig. 4, extreme right and left front edges of main fan). This, together with direct observation of field-generated flows, suggests that many truly dry grain-flows may also travel mainly by plug-flow, rather than by the usually cited process of fully distributive intergranular shearing (cf. Bagnold, 1954).

GEOLOGIC APPLICATION

(1) Large scale analogues

The scale of the phenomena described in this note is very small by comparison with any realistic geologic examples. As Johnson (1970, p. 437) has stressed, however, the similarity of morphology between such small-scale phenomena and the larger scale field descriptions available suggests that there may be close similarity of process between the two extremes. It is therefore interesting to briefly comment on the type of sedimentary deposits that might result from application of the processes described in this paper to a larger scale model; for example, to the building of a submarine fan several kilometres across somewhere on the continental slope.

Several conspicuous features might be expected to occur in the deposits of such a fan. They include: (1) sand-granule grain sizes would characterize the bulk of the sediments; (2) bedding characteristics would be extremely variable, with appreciable numbers of thick but composite beds (*sensu* Hendry, 1973, and see also (2) below) reflecting closely successive flow events; (3) the majority of sedimentary structures would be those produced by mass-transport (cf. Fisher, 1971), but appreciable amounts

of traction emplaced or reworked sediment could occur either within or between composite beds if significant bottom currents were active on the fan; (4) the fan deposits should interdigitate with deep-sea or basin-floor sediments at their extremities (that is, should generally be associated with flysch sequences); and (5) the larger scale of our imaginary example might be expected to result in appreciable amounts of coarser detritus (including some penecontemporaneously derived) becoming incorporated in the mass-transported fan sediments as breccia or conglomerate components.

Many sedimentary occurrences described in the literature as 'fluxoturbidite' or 'proximal sandy flysch' facies possess many or all of the attributes listed above, and rather than cite a number at random I leave it to the readers' field experience to provide a familiar example. A recently described occurrence of Oligocene, continental margin, submarine canyon and fan facies from southern New Zealand is the example most closely known to the author (Carter & Lindqvist, 1975). As described in that publication, granular sands and breccia-sands of lithofacies B_{1-3}, and possibly lithofacies C, were partly or largely emplaced by mass-transport processes similar to those described here from a small-scale Recent analogue. It seems likely that the description of such mass-flow facies in proximal redeposited sedimentary environments will increase, and also that some presently known examples of 'proximal' or 'sandy' flysch will be redescribed and reinterpreted in the future as mainly emplaced by mass-flow.

(2) **Generation of composite beds**

The common occurrence at Mararoa of retrogressive flow slides, whereby successive pulses of mass-flowing sand are mobilized downslope along the same route, supports Hendry's (1973) suggestion that mass-flows generated in such fashion result in emplacement of amalgamated or composite sand beds. As seen in many proximal flysch sequences (Fig. 9), composite beds are commonly between ½ and 2 m thick, of coarse to very coarse sand grain sizes, and occur in packets within turbiditic flysch. The packets of composite but thick-bedded sand are often interpreted as channelized or fan deposits, and typical examples have been described by Ballance (1964) and Hendry (1973). Sub-units within a composite bed are demarcated by sharp and conspicuously irregular bases, usually inferred to be erosive, above which occurs an abrupt increase in grain-size, often to granular very coarse sand; when traced laterally, such subunit surfaces occasionally merge or disappear. Mudstone clasts are often present, sometimes concentrated within the basal coarser grained parts of the subunits. Subunits usually show a normal grading throughout, with a conspicuous concentration of granular or very coarse sand in the basal few centimetres; reverse grading occasionally occurs towards the top of a subunit. The thicker subunits generally pass up into parallel laminated fine to medium sand in which the parallel lamination shows varying amounts of synsedimentary hydroplastic deformation as well as occasional diapiric fluidization phenomena. Between 2 and 5 subunits may occur in composite beds that reach an overall thickness of up to 2 m (Fig. 9).

Though it is usually demonstrable that such composite beds have been mass-emplaced, there is often disagreement over the precise mechanism, some authors favouring turbidity currents while others argue for laminar mass-flow. Observation of the retrogressively propagating flow slides at Mararoa suggests a plausible explanation for such composite mass-transported beds. As a flow-slide propagates headwards,

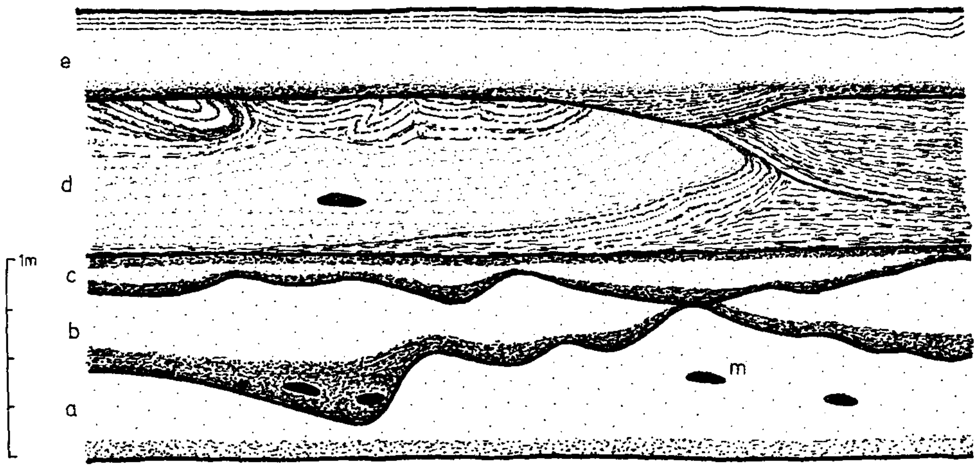

Fig. 9. Idealized sketch of a composite sand bed of the type inferred to be the product of successive pulses of a retrogressive flow slide (based on field sketches and photographs of examples seen in the Miocene Waitemata Beds, Auckland, New Zealand, and in Eocene flysch near Castiello de Jaca, Hacca-Pamplona basin, Spanish Pyrenees). (a, b) Initial and successive flow pulses with 'frozen' flow topography on their upper surfaces. Note mudstone clasts (m) and the apparently draped nature of the basal coarse grained layers (b) and (c) over this topography. (c) Successive flow pulse of similar type, but showing reverse grading towards the top. (d) Successive flow pulse of greater maturity (well developed grading, presence of good parallel lamination in upper part of subunit), probably reaching the fluxoturbidite flow stage; hydroplastic deformation induced during the final stages of bed deposition. (e) Final flow pulse, probably of fluxoturbidity type; note the oblique lamination produced by draped infill of the hollow on top of bed (d), and the incipient deformation of parallel lamination at top of bed (e). Though a, b and c are suggested to represent successive pulses from a single flow-slide, d and e may represent discrete, though closely consecutive, flows. The two major types of sand subunit, (a–c) and (d–e), may be present in various combinations and gradations in different composite beds.

successive pulses of sand are entrained downslope, and as each flow pulse slows or stops it is often almost immediately overridden by the following pulse or pulses. This suggests that the apparently 'erosive base' to each subunit within a composite mass-flow sand bed may rather represent the frozen topography of the *top* of the underlying subunit, which has been almost immediately overridden and infilled by a consecutive pulse derived from the same parent flow-slide as it propagated further headwards. Further, the coarse-grained detritus within the basal parts of successive subunits may reflect sorting of coarse material to the front and sides of a mass-flow (as observed widely in Recent and laboratory flows—cf. Johnson, 1970), where it is then overridden in crawler-tractor-like fashion by the finer material that comprises the bulk of the flow pulse. The two obvious alternative explanations of inter-subunit surfaces within composite sand beds both assume that the surfaces reflect erosion by the overlying bed, and are (1) a hypothesis of closely successive and erosive proximal turbidity currents; or (2) the alternation of mass-flows and powerful traction currents. The interpretation outlined before seems preferable to either of these alternatives, particularly since it is consistent with the unusually steep-sided nature of some of the topography on inter-subunit surfaces (cf. Fig. 9, slopes of up to 70° are common, and compare with the topography of the upper surfaces of the sand-fingers of Figs 5–7),

and because features indicative of either turbulent or traction sediment deposition are generally conspicuously lacking in the composite sand-beds under discussion.

(3) Other implications

Two further implications of the Mararoa sand finger-fans have been pointed out to me by Dr R. J. Norris. First, the plates clearly show (for example, Fig. 5) that extremely diverse local transport directions are characteristic, even between the several fingers of a single flow. Such an observation serves to strengthen the widely known but sometimes overlooked necessity for treating small samples of transport direction indicators with extreme caution. Second, though a large scale example of the Mararoa sand-finger fans would undoubtedly be termed a 'sandy', 'proximal', or perhaps 'fluxoturbidite' facies, it would be misleading to use the term 'channelized sand facies' (Stanley & Unrug, 1972). In the Mararoa fans at least, apart from the major channel that feeds the head of an individual fan, channels are conspicuous by their absence. The fans are in fact constructed as convex upwards sedimentary piles, and the bases of individual mass-flows are planar except insofar as they are cast into irregularities of the top surfaces of underlying flows. Therefore, though the term channelized sand facies may well be appropriate for some occurrences of sandy, mass-emplaced sediments, it will certainly not serve to cover all such deposits and hence should not be used as a general facies descriptor for 'sandy flysch' deposits.

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