Sedimentology (1975) **22**, 465–483

Sealers Bay submarine fan complex, Oligocene, southern New Zealand

ROBERT M. CARTER *and* JON K. LINDQVIST

Department of Geology, University of Otago, Dunedin, New Zealand

ABSTRACT

The Oligocene Balleny Group of Chalky Island, southwestern Fiordland, comprises a typical continental margin sequence 900 m in thickness. Thin nearshore traction deposited sediments at the base are overlain by submarine canyon and fan lithofacies that were deposited by the full range of subaqueous mass-transport processes. A steep-walled channel within Balleny Group is interpreted as a fossil proximal fan-channel. The sedimentary fill of the channel is texturally similar to sediments moving by slump-creep in Recent submarine canyons and fan-valleys. The field data presented indicate (1) that a small canyon complex at Sealers Bay was initially cut by subaqueous debris-flows derived from an adjacent cliffed continental coast; (2) that transport within the upper parts of the canyon and fan-channel complex was primarily by inertia-flow and slump-creep; and (3) that these more proximal types of mass-transport gave way gradationally and successively to fluxoturbidity and turbidity currents at locations further down-slope, with consequent deposition of sediment in more distal fan-channel and fan-surface environments as fluxoturbidites and turbidites, with lesser contributions from inertia-flows.

INTRODUCTION

The Balleny Group of Fiordland comprises the only sediments in southwestern New Zealand that belong to the regional Cretaceo-Tertiary sedimentary cycle (i.e. the Kaikoura Sequence, *sensu* Carter *et al.*, 1974). To date the sediments are known only from reconnaissance observations, those of Wood (1960) being the most recent. Though previously mapped as Cretaceous to Oligocene, Balleny Group is in fact entirely of early Oligocene age (Hoskins, in Carter & Lindqvist, 1975). Its deposition broadly coincided with the start of a phase of active flysch basin formation along the whole of the western side of the New Zealand continental block, during which a series of fault-bounded NNE–SSW troughs were depressed deeply below sea level and received a fill of mainly flysch type sediment. Many magnificent examples of proximal mass-flow sedimentation were produced, particularly during the early stages of basin formation, but, with the notable exception of the Waitemata Basin of the Auckland region (e.g. Ballance, 1974; Gregory, 1969), most remain sedimentologically

undescribed even at a reconnaissance level. A more detailed account of the regional setting, stratigraphy and tectonic significance of Balleny Group is presented elsewhere (Carter & Lindqvist, 1975). This present paper is devoted to the description of a spectacular channel that was penecontemporaneously cut in Balleny Group sediments, and also discusses some of the evidence for sedimentary mechanisms that acted within the Sealers Bay canyon-fan complex.

Note on terminology

The terminology for mass-transported and deposited sediments follows Sanders (1965) and Carter (1975), but a few key concepts will be briefly summarized here. Five major types of process are operative in mass-transported sediments, namely slurry-flow, grain-flow, slump-creep, fluxoturbidity currents and turbidity currents. (1) In *slurry-flow*, the moving sediment mass possesses enhanced viscosity, generally due to the presence of clay-grade fines that mix with the water within the flow to produce a continuous-phase slurry; this slurry, which has strength and is hence non-Newtonian in behaviour, may transport a large amount of material of sand or larger grain-sizes (when a large number of suspended clasts are present, the term *debris-flow* is often used). The process is similar to grain-flow in the viscous region of Bagnold (1954). (2) In *grain-flow*, the moving sediment consists of granular material in water of normal, or near-normal, viscosity. Transfer of momentum takes place by actual collisions between grains, which produces a dispersive pressure; this is grain-flow in the inertial region of Bagnold (1954). For many clearly mass-transported sediments it is not possible to infer whether a given-bed was strictly emplaced by slurry-flow or grain-flow; in these cases, the collective term *inertia-flow* is useful (Sanders, 1965). Beds or facies that are inferred to have been emplaced by fluid inertia-flow are termed *flowites* (Carter, 1975). (3) In *slump-creep*, so far only demonstrated in sediments constrained within Recent submarine canyons and fan-valleys, sediment is transported downslope by a semi-continuous process of slumping, retrogressive flow sliding, and slow creep (Shepard & Dill, 1966). The channel fill acts essentially as a 'sand-glacier', serving to erode and abrade the substrate as well as being a major cause of downslope sediment transport. (4) The term *fluxoturbidity current*, as fluxoturbidite, was first proposed by Kuenen (1958) for a process of bed-shearing inertia-flow that was observed experimentally at the base of very thick turbulent suspensions (Kuenen, 1951, 1958; see also Hampton, 1972). Middleton (1967) later showed that a similar process was possible by grain-flow *sensu stricto*, and the term fluxoturbidity current is conveniently extended to cover it (Carter, 1975). This usage of fluxoturbidity current, and fluxoturbidite, differs from that of most other recent writers, who generally use the term as a general facies descriptor, following Dzulynski, Ksiazkiewicz & Kuenen (1959). (5) The term *turbidity current*, and turbidite, are used in the conventional sense, i.e. for the transport of sediment within a fully turbulent suspension.

SEDIMENTARY SETTING

Balleny Group (Fig. 1) represents a broadly transgressive sedimentary sequence that accumulated along the edge of a rapidly downwarping, or faulting, continental margin. A thin basal wedge of traction-deposited intertidal and shallow continental

'shelf' sediments (Puysegur Formation) is overlain by probable submarine canyon deposits (Nuggets Formation); deep-sea fan sediments follow (Sealers and Munida Formations), and pass up gradationally into chalk marls with spaced thin turbidites (Chalky Island Formation) that represent distal fan and possibly abyssal sea-floor deposits. The total thickness of sediment comprising Balleny Group is 900 m+, and microfossils indicate an Oligocene age (Whaingaroa oppelzone). A modern analogue of the environments represented by these sediments can be found in the Rio Balsas canyon system, and particularly its associated littoral facies, off western Mexico (Reimnitz & Gutierrez-Estrada, 1970).

The sediments of Balleny Group have been divided into a number of broad sedimentary lithofacies. Lithofacies A_{1-3} characterize the traction deposited sediments of Puysegur Formation, lithofacies E applies to Munida Formation medium-bedded turbidite sandstones interbedded on about a 1:1 ratio with interturbidite calcareous muds, while lithofacies F corresponds to the Chalky Island Formation nannoplankton chalk marls with spaced thin sandstone bands of distal turbidite origin; a more detailed treatment of these lithologies is contained in Carter & Lindqvist (1975).

The stratigraphically intermediate Nuggets, Sealers and Munida Formations comprise a complex series of mass-flow deposits (breccias, breccia-conglomerates, breccia-sands), fluxoturbidites and turbidites characterized under a further six major lithofacies.

Lithofacies B_1 (Nuggets Formation)

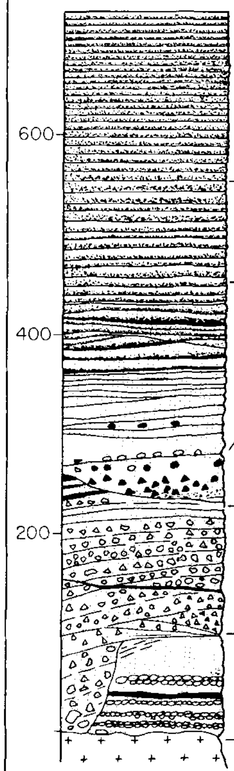
Facies B_1 comprises poorly sorted, internally unstratified angular to subangular breccias with a matrix of coarse to granular arkosic sand, generally with beds between 1 and 3 m thick. The provenance of constituent clasts is overwhelmingly local, and the presence in some beds of oyster debris (*Pycnodonte* sp.) indicates marine deposition. The breccias occur interbedded with lithofacies B_2 and B_3. They are inferred to have been emplaced dominantly by inertia-flow, largely through debris flows or by direct emplacement by rockfall, on subaqueous breccia-conglomerate fans and within the heads of small submarine canyons.

Lithofacies B_2 (Nuggets Formation) (Figs 2, 3)

All gradations occur between dominantly breccia beds characteristic of facies B_1 to matrix-supported breccia-sands of facies B_2. Lithofacies B_2 is characterized by massive to poorly laminated granular medium to coarse arkosic sands, with isolated blocks, lenses and layers of matrix-supported breccia. The sandstones are very poorly sorted, with a continuous gradation of grain size across all the sand grades to granules and pebbles. Bedding is poorly defined, but a diffuse parallel lamination pervades most beds, which appear to be composite in that they contain intra-bed indications of channelling (cf. Fig. 3). Beds may be up to 10 m thick, and the constituent clasts generally have their long-axes parallel to bedding. It will be argued that this lithofacies was at least partly emplaced by slump-creep (see also C below).

Lithofacies B_3 (Nuggets Formation) (Fig. 4)

This facies comprises thin to medium-bedded coarse to granular arkosic sands. Grading is present but not always normal, sometimes going from reverse to normal in a single bed. Bed-contacts are poorly defined, particularly when there is little or no mud



Description	Diagnostic features	Depositional environment	Transport mechanism
Chalky Island Formation Chalk with abundant *Zoophycus* and *Anemonichnus* ½–5 cm beds graded fine sand to silt, with parallel lamination and/or ripple cross stratification. Some thicker sands up to 1½ m, with loaded sole markings. Horizons of rubbly bedded chert	Terrigenous poor pelagites Thin turbidites Trace fossils Sand:marl = 1:100	Distal fan – ? Abyssal plain	Hemipelagic fallout and distal turbidity current
Munida Formation 5–100 cm units of graded coarse to fine sand Interbeds of green-grey marl	Silty pelagites. Thick turbidites with Bouma sequences Bioturbation of sandstone tops Sand : marl = 3:1 to 1:1	CONTINENTAL RISE: Distal fan	Turbidity currents
Sealers Formation 20–100 cm very coarse to coarse granite derived sands with bioturbated sandy mudstone interbeds Isolated boulders in otherwise uniform sand beds	Crude grading Bouma sequences rare Low angle channels	CONTINENTAL RISE: Fan	Mainly fluxoturbidity currents
Channel fill very coarse to granular arkosic breccia sands with mudstone clasts to 1½ m Associated thin–medium bedded sands and *bioturbated slightly calcareous sandy mudstones*, and thick to very thick bedded granular arkosic sands, some with floating clasts	Mudstone clasts Steep-walled channels Thick structureless sands with scattered clasts	CONTINENTAL SLOPE: Proximal fan	Mass-flow (including slump-creep) and fluxoturbidity current
Nuggets Formation Coarsely bedded breccias and breccia sands	Poor bedding and sorting Lack of traction features Olistoliths	CONTINENTAL SLOPE: Canyon (locally coastal cliff or subaqueous fault scarp fans)	Mainly mass-flow
Puysegur formation Medium–coarse cross-bedded arkosic sands Polymict roundstone conglomerates and sands with thalassinidean burrows Water worn surface, residual boulders	Trace fossils Traction features Rounding and sorting	SHELF: Shoreline wedge	Traction
Granite basement			

Fig. 1. Summary stratigraphic column and environmental and depositional interpretation of the sediments of Balleny Group, Chalky Island.

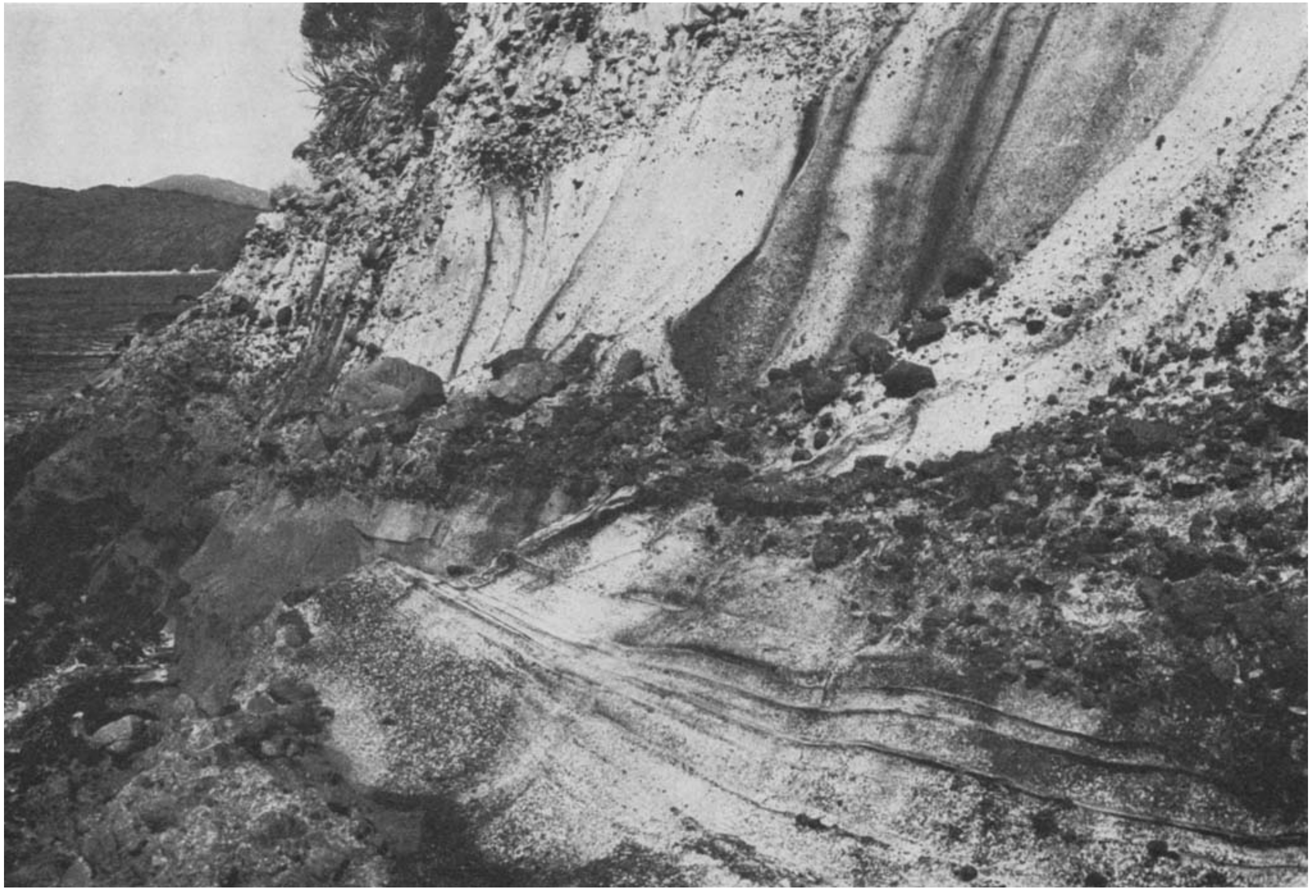


Fig. 2. Typical breccia-sands of lithofacies B_2 (Nuggets Formation). Note the angular nature of the larger clasts and their diffuse distribution. A wedge of thin-bedded granular to medium sands, probably of grain-flow origin, occurs at lower right. View east at Breccia Point, Chalky Island; Sealers Bay in left background. Height of section about 6 m.

Fig. 3. Poorly laminated breccia-sands of lithofacies B_2 (Sealers Formation). Note the isolated layers and lenses of breccia, the orientation of long axes of clasts parallel to bedding, and the presence of diffusely demarcated channelling (centre). Locality, shore cliff, easternmost corner of Lunch Bay. Height of section about 8 m; large clast to centre-right about 80 cm across.

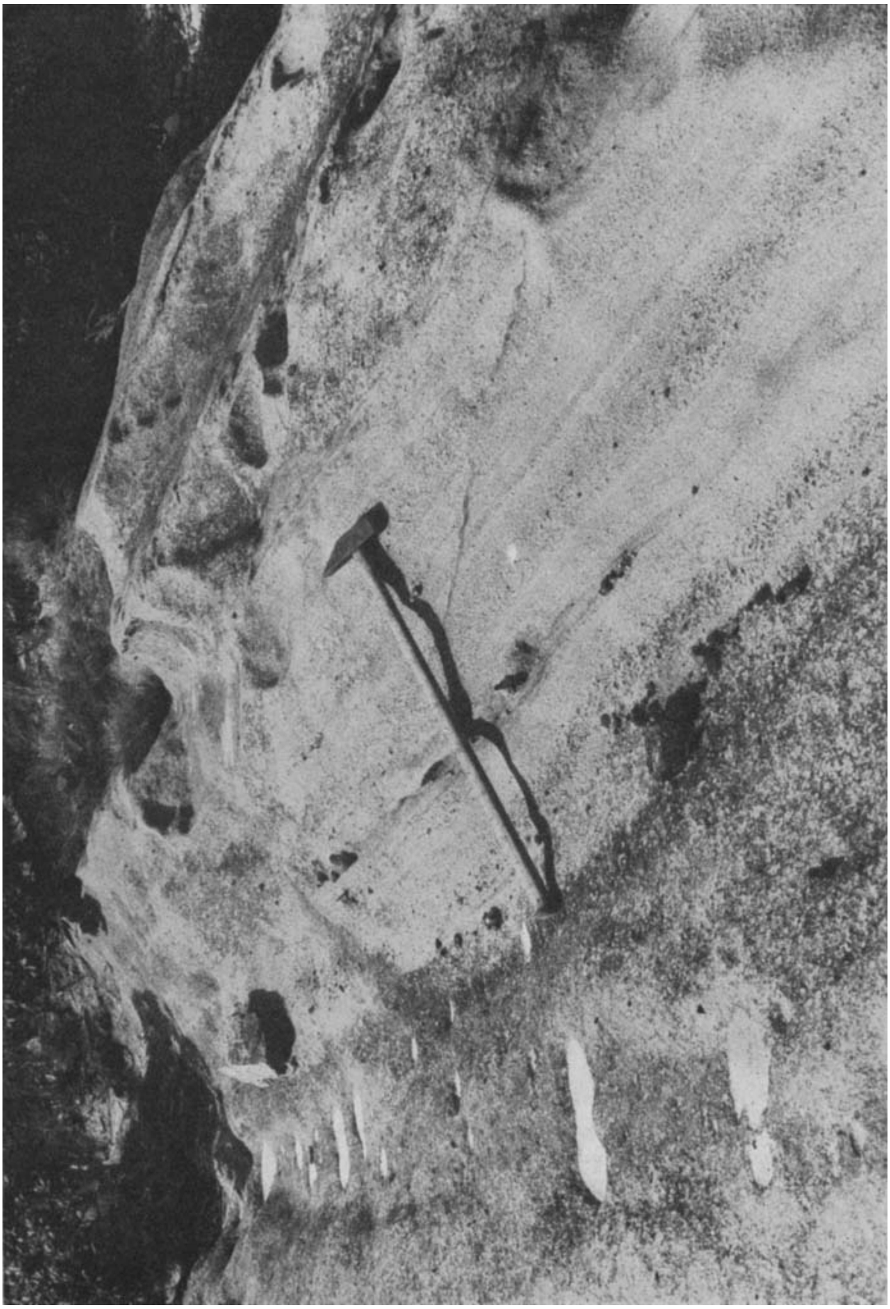


Fig. 4. Diffusely laminated thin-to medium-bedded arkosic sands of lithofacies $\mathbf{B}_3$ (Nuggets Formation). Note the presence of large dispersed clasts, the poorly defined bed-margins, and the presence of normal and reverse grading within the same bed (centre, 20 cm below hammer head). Locality, shore outcrop on east side of Sealers Bay, about 200 m south of Sealers Point. Hammer 85 cm.

or silt between sand layers. The sands contain isolated angular clasts that are large relative to bed thickness, and beds may pass laterally into layers or patches of poorly sorted breccia. Emplacement is inferred to have been by inertia-flow, generally by grain-flow *sensu stricto*.

Lithofacies C (Sealers Formation)

Thick sand units, between 3 and 10 m thick, are similar in all respects to the sands in lithofacies B_2 of Nuggets Formation except for the smaller amounts of terrigenous breccia they contain, and for the invariable presence of large penecontemporaneously derived mudstone clasts (cf. Fig. 7). It will be argued that this facies was largely emplaced by inertia-flow and slump-creep.

Lithofacies D_1 (Sealers Formation) (Fig. 5)

These very characteristic thick to very thick bedded sands have a sand : mud ratio of about 20:1, sometimes contain scattered 'floating' clasts of relatively large size, and are probably fluxoturbidites. Grain size is again medium to very coarse or granular sand, coarse-tail grading is poorly but consistently developed and Bouma sequences are generally absent.

Fig. 5. Thick-bedded poorly graded sands with scattered clasts, lithofacies D_1 (Sealers Formation). Two sand units separated by a thin muddy sandstone. Note the presence of obscure? antidune cross-stratification above and to left of hammer. Locality, Sealers Bay, a little further south than Fig. 4. Hammer (slightly foreshortened) 85 cm.

Lithofacies D_2 (Nuggets and Sealers Formation) (Fig. 6)

This lithofacies comprises thin to medium bedded sands and muds with a sand : mud ratio of about 2–6 : 1, though the mud part of each couplet is usually very sandy due to extreme bioturbation. The beds are generally of very coarse to medium sand grain size, poorly graded, and contain displaced shallow water fossil debris. Though rare,

Fig. 6. Thin to medium-bedded flysch of lithofacies D_2 (Sealers Formation). Note the presence of diffuse parallel lamination, the sharp flamed bases to the sandstones and the thin and bioturbated nature of the inter-sand sandy mudstones. Locality, east side of Sealers Bay, wave undercut and cleaned surface at south end of middle large cliff. Pencil 16 cm.

Bouma sequences seen in the sands include T_{a-c}, T_{a-b} and T_{b-c}, suggesting that lithofacies D_2 was deposited mainly by turbidity currents.

SEALERS BAY CHANNEL (Figs 7–10)

Large channel features are not uncommon in proximal flysch deposits, and have been described by many writers. Rarely, such channels are of sufficient magnitude to suggest they represent major sediment feeder routes similar to present-day canyon or fan-valley channels (Stanley & Bouma, 1964; Walker, 1966; Jacka *et al.*, 1968; Kelling & Woollands, 1969; Normark & Piper, 1969; Piper & Normark, 1971; Hall & Stanley, 1973; Whitaker, 1974). Sealers Bay Channel is a further such feature, and in many respects is closely similar to the Miocene Doheny Channel described by Normark & Piper (1969), and to the channels associated with the Caban Conglomerates of Kelling & Woollands (1969).

Sealers Bay Channel is magnificently exposed in cliffs on the east side of Sealers Bay, Chalky Island (see map in Carter & Lindqvist, 1975). The main channel is part of a complex, superposed sequence of shallower channel features (cf. Fig. 10), of which at least five are visible in Fig. 7. The main channel is some 40 m wide, and at least 5 m deep, though the base is below beach level. In addition to the obvious channels, the sequence shows complex lensoid interbedding of the lithofacies previously described. The following generalizations apply:

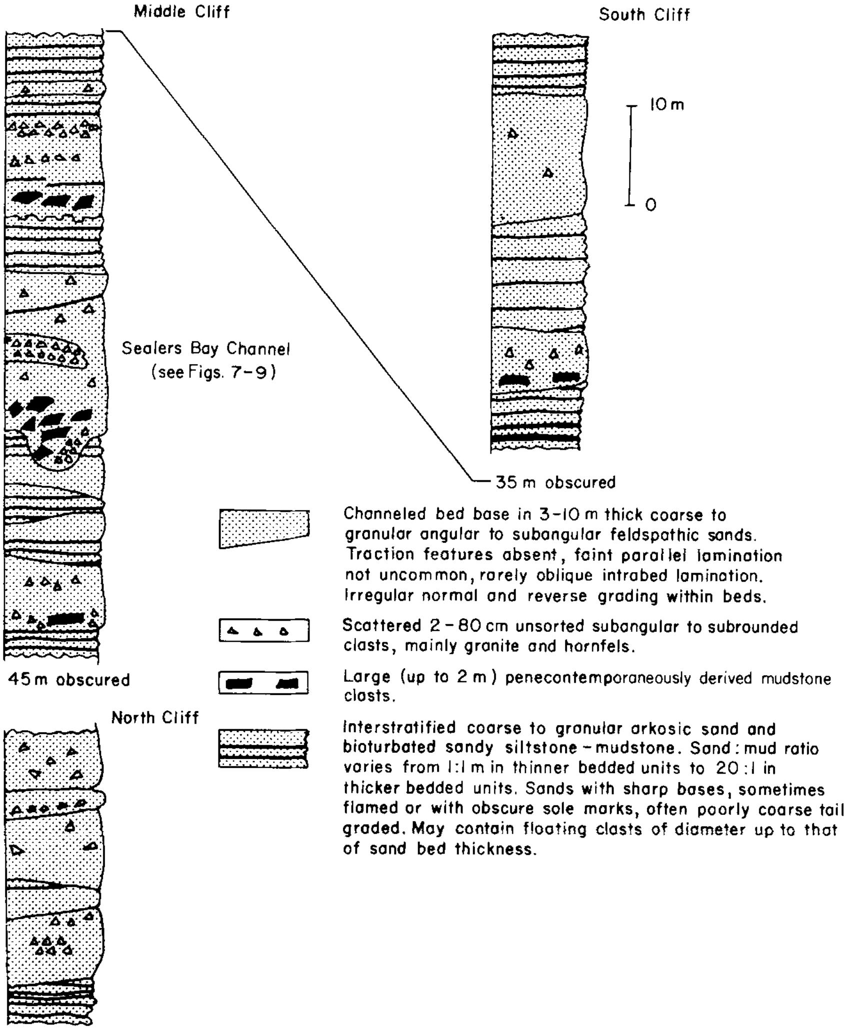


Fig. 10. Measured section across main Sealers Formation outcrops on east side of Sealers Bay. Middle Cliff corresponds to the outcrop of the main Sealers Bay Channel (cf. Figs 7–9).

(1) The major channels are generally cut into thin-bedded flysch of lithofacies D_2: deeply incised channels may cut through lithofacies D_2 into underlying thick-bedded fluxoturbidite or inertia flow sands and breccia (lithofacies D_1 or C).

(2) Channel fill generally commences with a thick unit (30–70% of total fill) of sands and breccia sand of lithofacies C, with minor inertia-flow conglomerates; this is overlain in some cases directly by thin-bedded sands (D_2), or sometimes by thick-bedded sands (D_1, fluxoturbidite) followed by D_2. The channel-fills are therefore broadly thinning and fining upward sequences (cf. Walker & Mutti, 1973).

(3) There is no difference in consolidation of the sediments forming the channel walls and those forming channel fill, suggesting that the channels were cut in unlithified sea-floor sediments.

Fig. 7. Panorama of the axis of Sealers Bay Channel as exposed in shore cliffs on the east side of Sealers Bay. Note the following features (as indicated on photograph): the presence of at least five superposed channel features (1–5); the north and south walls of the main Sealers Bay Channel (N and S, respectively); the presence of large mudstone clasts in the thick channel-fill sands (m); diffuse patches of breccia in matrix-support (bm), some grading laterally into homogeneous grain-supported conglomerates (bg); diffusely demarcated intra-bed channelling (ch); the presence of lithofacies C and D_2. Figure (left of centre) gives scale.

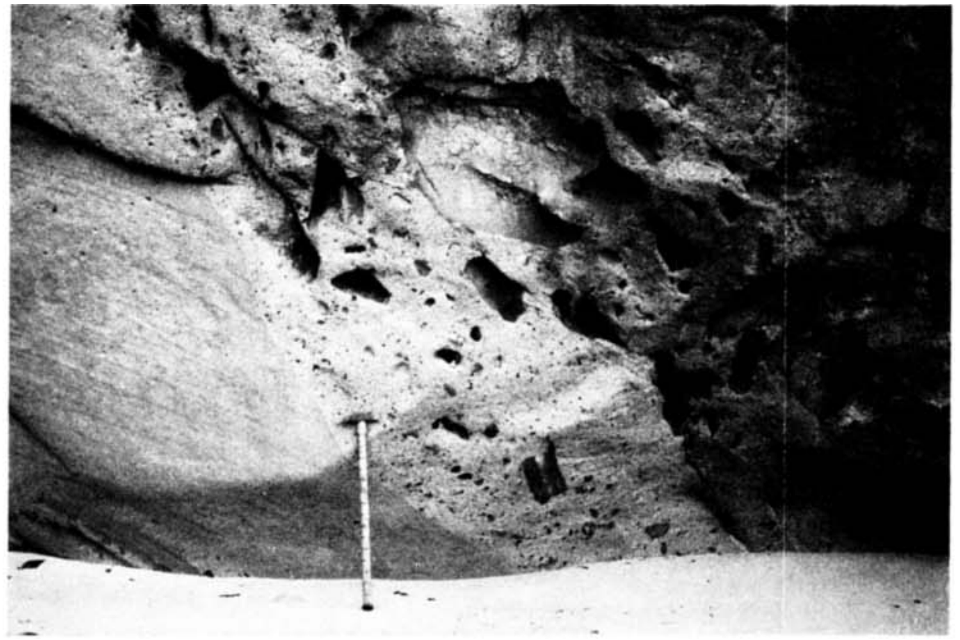


Fig. 8. Close-up of north wall of Sealers Bay Channel. Wall cut in diffusely laminated sands of lithofacies C or D_1 (pull-apart mudstone clast lower left). Channel fill of granular very coarse sands with numerous mudstone clasts, lithofacies C. Hammer 85 cm.

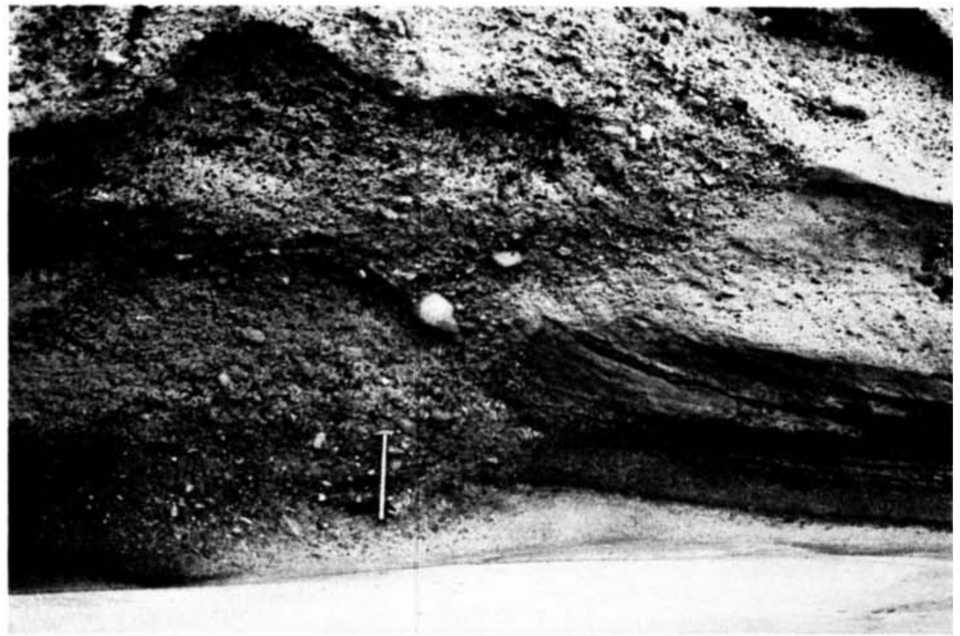


Fig. 9. Close-up of south wall of Sealers Bay Channel. Wall cut in medium to thick-bedded sands of lithofacies D_1. Channel fill of granular coarse sands with abundant terrigenous clasts. Hammer 85 cm.

(*Facing page* 474)

ENVIRONMENT OF DEPOSITION OF SEALERS BAY CHANNEL

It is clear that the tendency for rhythmic repetition of lithologies just described represents the cutting and filling of successive submarine channels, following a pattern similar to the generalized models suggested by Normark & Piper (1969), Normark (1970) and Lowe (1972). Though the overall stratigraphy and outcrop relations suggest that the Sealers Bay Channel represents environments distal to the feeding canyon system, it is difficult to be sure of its precise position on what was clearly an active fan since most descriptions of modern fans are based on geomorphically long-established sedimentary systems. However, comparison with the most recent descriptions of modern and inferred fossil fans (Normark, 1974; Nelson & Nilsen, 1974; Mutti, 1974) suggests that the channel represents a major feeder in the area of transition between the leveed valley on the upper fan and the actively outbuilding suprafan. Normark (1970) has stressed that 'fan-valleys are very broad shallow features (1–5 km wide)' and the narrowness and deep incision of the Sealers Bay Channel therefore preclude that particular interpretation; furthermore, the absence of really typical muddy-silty levee deposits is also inconsistent with a major leveed fan valley. The sand-dominated sediments with which the channel is immediately interbedded (Fig. 10) show abundant low-angle channelling, consistent with their representing an irregularly braided channel-distributary system similar to that suggested for Recent suprafans (Normark, 1970, 1974). We conclude that the extremely 'proximal' nature of the Sealers Bay Channel fill suggests the feature represents an incised and active channel that led out of the leveed valley of the upper fan and onto the suprafan, a conclusion similar to that reached by Piper & Normark (1971) in their interpretation of the Doheny Channel.

SEDIMENTARY MECHANISMS WITHIN SEALERS BAY CHANNEL

As might be expected for sediments deposited in such proximal fan environements, mass-transport processes were responsible for the emplacement of most of the sediments. Though the total absence of traction produced sedimentary structures is perhaps surprising, abundant evidence for mass-transport, and specifically for grain-flow, slurry-flow, slump-creep and fluxoturbidity and turbidity current transport, can be found. This evidence is discussed further below.

The channel sands (lithofacies C)

Since the discovery of the phenomenon of intra-submarine canyon grain-creep almost ten years ago (Dill, 1964; Chamberlain, 1964) there has been a tendency to discount creep as a viable mechanism of sediment transport in fossil flysch deposits, mainly because the mechanics of the process remain mysterious and because of the impression that creep can only operate on excessively steep slopes (Walker, 1967; Middleton, 1970; Walker & Pettijohn, 1971). However, observations such as those of Shepard, Dill & von Rad (1969; summarized in more detail in Carter, 1975) suggest that creep in fact takes place even on relatively gentle slopes in fan valley environments. As documented by Shepard & Dill (1966), grain-creep seldom acts alone as a sedimentary mechanism, but is intimately associated with semi-continuous downslope

slumping on all scales, with true sand-falls spilling in from hanging tributary valleys, and also with more 'catastrophic' processes such as rock-fall from the channel sides and emplacement of coarse grained debris-flows or gravel-flows along the main channel axis. There is, therefore, no such thing as a 'pure' grain-creep sediment, only a complex mixture of sands and breccias that are collectively and slowly moving down the channel axis by a mixture of creep, retrogressively propagating sand-flow, grain-flow and slurry-flow, with constant additions of sediments of all grain-sizes from channel walls and tributaries.

No single attribute is typical of either Recent slump-creep deposits, or of the occurrences here interpreted as their fossil equivalents, but the following features are all found in the sediments associated with Sealers Bay Channel; taken together they delineate a unique sedimentary facies whose closest modern analogue is found in the creeping-slumping 'sand-glaciers' in the head of nearshore submarine canyons (see also Stanley, 1967; Stanley & Unrug, 1972).

(1) An intimate association with fluxoturbidites and levee (overspill) turbidites, yet a general absence of any of the typical features of turbidity current emplacement in the slump-creep beds themselves.

(2) The presence of a pervasive parallel lamination that is subtly different from conventional bedding, and attributed to laminar shear during emplacement (Stauffer, 1967; Middleton, 1970).

(3) The inclusion of exotic clasts, whose distribution encompasses the complete range from coherent clast-supported patches (Fig. 7), to scattered matrix-supported clasts (Figs 7 and 9). Clasts may range up to 5 m, but sizes up to about 1 m are most common. When matrix-supported, the clasts generally have their long axes parallel to bedding (Fig. 3).

(4) The inclusion of abundant penecontemporaneously derived mudstone clasts (Figs 7 and 8), probably incorporated partly by substrate and wall 'plucking' by the channel fill, and also by direct rockfall from the channel sides onto the channel fill.

(5) Where the coarser clasts are gathered together into local patches, lenses, or relatively homogeneous clast-supported beds, the margins of the aggregations are nearly always gradational; good exposures demonstrate that even apparently homogeneous clast-supported conglomerate beds have extremely diffuse boundaries that are laterally gradational to more typical sand with scattered clasts (Fig. 7). Presumably these beds were first emplaced by rapid inertia-flow, but later lost their identity as a result of intra-bed shear within the moving channel-fill.

(6) The almost complete absence of regular intra-bed features. Rarely, oblique bedding delineates diffuse channel-like structures (Figs 3 and 7); the draped (or 'catenary'—cf. Whitaker, 1962) fill is identical to the material outside the 'channel', there is generally no channel-lag, and the features are entirely unlike typical channels cut and filled by traction processes.

(7) The presence of a complete range of poorly sorted sand-granule, and larger, grain sizes, and the absence of appreciable mud content.

Though many of the characteristics listed above are common to models of sedimentation involving rapid inertia-flow, such models (e.g. Middleton & Hampton, 1973) usually predict a sequence of internal bed forms, whilst admitting that the sequence may be irregularly represented. It should therefore be stressed that it is points 4–6 above that are particularly critical in suggesting a slump-creep emplacement for

the fill of Sealers Bay Channel. The great bed thickness without signs of major intra-bed amalgamation, the presence of irregularly streamlined layers of large mudstone-siltstone clasts, and the fact that discrete sharply bounded conglomerate layers pass laterally into structureless sand with diffusely scattered pebbles, are all features that seem inconsistent with emplacement by rapid inertia-flow, at least so far as it is conventionally pictured (Sanders, 1965; Stauffer, 1967; Middleton & Hampton, 1973). Perhaps the most obvious alternative to slump-creep is emplacement by submarine avalanching (cf. Jacka *et al.*, 1968), but such a chaotic mode of emplacement would not account for all of the features shown by the fill of the Sealers Bay Channel, a particular difficulty being the 'sharply bounded' to 'diffusely scattered' changes in thick intra-channel conglomerate units.

Interpretation of Balleny Group sediments as slump-creep deposits is made most confidently, and even then with reservations, for the fill of Sealers Bay Channel (lithofacies C). However, some occurrences of lithofacies B_2 (e.g. Fig. 3) have features difficult to explain solely by a grain-flow mode of origin, and it is possible that lithofacies B_2 has been in part affected by penecontemporaneous slump-creep. A general lack of detailed bed descriptions makes assertions difficult regarding the slump-creep nature of proximal flysch sequences described in the literature. However, the 'chaotic sands' recorded as fill within the Doheny Channel (Piper & Normark, 1971), and the 'avalanche deposits' of the Bell Canyon Formation (Jacka *et al.*, 1968) would repay further examination with this possibility in mind.

Thick to very thick-bedded sands (lithofacies D_1)

Comparison of Fig. 13 of Carter & Lindqvist (1975) with Fig. 7 of Stanley (1971) reveals an extremely close similarity between lithofacies D_1 and the characteristic 'channelized sand' deposits of the Annot Sandstone, French Maritime Alps. These sediments have been well described in a number of papers (e.g. Stanley, 1967; Stanley & Bouma, 1964). Walker (1967) has argued that strata of this type are indistinguishable from proximal turbidites, but they are here interpreted (mainly after Sanders (1965) and Stauffer (1967)) as fluxoturbidites in the sense defined by Carter (1975), i.e. as having been deposited from the inertia-flow bed-load of fluxoturbidity currents. Their uniformity of thickness across large outcrops suggests they are unlikely to have been deposited from true sand-flows as observed in Recent canyons (which generally result in localized and wedge-shaped deposits), and the more extensive high velocity flowing grain-layers hypothesized by Sanders (1965) and Stauffer (1967) have not yet been identified in the natural environment nor generated experimentally in the absence of an overlying impelling turbidity current. Furthermore, occasionally a constituent bed within a bundle of thick-bedded fluxoturbidite strata conforms exactly to a Bouma T_{a-c} turbidite, thus demonstrating the passage of occasional turbidity flows *sensu stricto*.

Thin- to medium-bedded sands and muds (lithofacies D_2)

Interpreting the deposition of thinly bedded flysch lithofacies D_2 is difficult, though there is little doubt that the facies is largely or entirely redeposited. From a distance the rhythmic sandstone-mudstone alternations, and the bed thicknesses of 5–10 cm, suggest 'distal' turbidite deposition. However, close examination usually reveals that the sandstones are rather coarse grained for such an interpretation, often very coarse sand, and grading is generally poor and sometimes absent.

At least some packets of lithofacies D_2 contain sharp-bottomed graded beds showing Bouma T_{a-c} or T_{b-c} sequences (Fig. 6) and are turbidites, or possibly thin fluxoturbidites. Furthermore, some of these occurrences are apparently in channel-wall situations with respect to laterally equivalent channel-fill breccias and breccia-sands, as in one example in Boulder Bay, Chalky Island (see map, and Fig. 15, in Carter & Lindqvist, 1975), and are thus possible levee deposits in spite of their coarse grain size and lack of Bouma sequences commencing with T_c.

Other occurrences of facies D_2, such as at the top of the north wall of the Sealers Bay Channel (Fig. 7), are also in levee position but lack Bouma sequences, and are somewhat poorly graded and often difficult to distinguish from the inferred thin grain-flow facies B_3. From the reconnaissance field data at hand we are unable to decide whether this particular occurrence represents channel overspill (levee) deposits or not, but the fact that the south wall of the channel is in medium bedded sands of lithofacies D_1 (Fig. 9) perhaps argues against a levee interpretation of the thinner-bedded sands of the north wall.

EVIDENCE FOR THE PRESENCE OF SMALL SUBMARINE CANYONS

Submarine canyon walls have not yet been seen in outcrop in the Chalky Island region, but the general sedimentary setting of Balleny Group demonstrates it to have been a fairly typical continental margin shelf-canyon-fan sedimentary complex. However, a major difference between the Chalky Island sequence and most modern fans is that sedimentation at Chalky was initiated by the rapid onset of local tectonism. Some of the coarse mass-transported breccia-conglomerates of Nuggets Formation therefore might represent subaqueous fans that built directly out on the downthrown side of major faults. In fact, Oligocene sediments representing such fans are known from the Waiau trough, a major sediment-filled graben fringing the eastern side of the Fiordland block (Wood, 1966; Carter & Norris, in preparation). However, most of the Chalky Island breccia-conglomerates and breccia-sands are here interpreted as representing submarine canyon fill, even though fanglomerate facies may also be represented within Nuggets Formation. Evidence for the presence of small submarine canyons at Chalky includes the following.

(1) The general consideration that the abundantly represented sandy fan sediments are likely to have been funnelled from continent to deepsea via intermediate feeding conduits; on modern shelves such conduits are represented by submarine canyons.

(2) Immediately to the east of Chalky Island, on mainland Gulches Peninsula, thick structureless coarse breccias lie directly on basement, cutting out the shelf facies Puysegur Formation, and thus at least 80 m of local, and probably channelled, relief may be inferred on the Nuggets-Puysegur Formation contact (some distance further east again, in the region of Puysegur Point, the Puysegur Formation is appreciably thicker; thus 80 m is very much a minimum figure for the relief of this contact).

(3) In Boulder Bay, on the north coast of Chalky Island, the thick sequence of crudely and coarsely bedded breccias and breccia-sands that make up Finger Rocks apparently abuts sharply against thin-bedded flysch of lithofacies D_2; though the contact is not visible, it is probably a 'channel' wall with at least tens of metres relief.

CANYON-FAN SEDIMENTATION MODELS

Accepting the presence of a submarine canyon complex through which passed the bulk of the sediment that now comprises Balleny Group, it is pertinent to ask: how were the canyon-fan couplets first established and what sedimentary mechanisms acted within them? Following Normark & Piper (1969) and Lowe (1972), it is useful to recognize three basic stages in the evolution of a typical submarine canyon and fan-valley complex; they are the formational, functional and filling stages respectively.

Formational stage

Breccia-conglomerates and breccia-sands of lithofacies B_1 and B_2 occur down to the base of Nuggets Formation, where they comprise over 90% of the sediment volume. Since these breccias are inferred to cut deeply into the nearshore sands of the Puysegur Formation they probably represent proximal canyon deposits that accumulated up to the very head of the Sealers canyon system. The minor turbidite-type sediments that also occur in Nuggets Formation are mainly lithofacies D_1, i.e. are inferred to have been deposited from sediment-laden fluxoturbidity currents with a basal inertia-flow carpet. Several writers have suggested that such a carpet would form a barrier between the current and substrate, inhibiting its erosive capacity (Hsu, 1959; Dzulynski & Sanders, 1962; Walker, 1966), and it therefore seems unlikely that these, anyway infrequent, fluxoturbidity currents were responsible for the major cutting of the canyon heads.

The breccia lithofacies of Nuggets Formation were ultimately derived from a nearby steeply cliffed shoreline. Direct evidence for this is seen on the south side of Gulches Peninsula, where Nuggets breccias interfinger to the east with coaly marginal marine facies of Puysegur Formation, but thicken to the west to abut and overlap a fossil cliff preserved in basement granite. Since the stratigraphic evidence from Chalky Island conclusively shows that a narrow nearshore wedge of sandy 'shelf' sediments fringed the Oligocene coastline in this region, it is thus clear that this 'shelf' would have received fairly frequent mass-flows deriving from the nearby shoreline cliffs. The effect of a large debris-flow armoured with clasts up to several metres in diameter on an unconsolidated sandy seafloor is not hard to imagine; as they crossed the shelf at least some of the flows would plough deeply and erosively into the substratum. The thinness of Puysegur Formation indicates that the shelf-break was fairly near shore, and as such debris-flows spilled off the landmass and across this narrow shelf they would precipitate slumping and flowing of sand where they crossed the shelf edge. It is concluded that, so far as field evidence is concerned, the Chalky canyon complex is most likely to have been initiated by highly erosive clast-armoured debris- and gravel-flows, combined with slumping and sliding of shelf-edge sands (cf. Stetson & Smith, 1938). A similar mode of origin has been argued recently for at least some modern canyons (Scholl *et al.*, 1970).

Functional stage

Canyons and fan-valleys serve as the major dispersal routes for sediment to travel from continents to ocean floors. Therefore the cutting of a canyon-fan channel is

followed by a stage during which it acts as a downslope sediment funnel and accumulates little permanent sediment within its axis (Lowe, 1972). If lithofacies D_2 is correctly identified as locally representing channel overspill (levee) deposits, then its presence topping the walls of a channel will provide the only direct evidence at that place for the passage of currents in the adjacent channel.

The thick- to very thick-bedded fluxoturbidites characteristic of lithofacies D_1 are mainly confined to Sealers Formation, and become increasingly abundant higher in the formation. They are interpreted as the moxt proximal channel-axis deposits of the turbidity currents responsible for the emplacement of the levee turbidites. Considering the highly sediment laden nature of these currents, they are unlikely to have arisen outside the canyon-fan channel complex, e.g. as direct turbid underflow from nearby rivers (Heezen & Hollister, 1971) or as storm generated rip currents (Reimnitz, 1971; Jacka *et al.* 1968). If they originated within the canyon-fan channel complex then they are necessarily derived from slumped portions of channel-fill sands, or directly from the canyon-fan channel walls, for these are the only more proximal sources of sand of sufficient magnitude. Furthermore, the grain-size range is well above that at which thixotropic mechanisms operate, or at which depositional metastability is likely to give rise to later spontaneous liquefaction; therefore, and as has been inferred for the sands in the heads of the California canyons (Shepard, 1951; Shepard & Dill, 1966), downslope sediment displacement was probably initiated by failure of the canyon axis fill consequent upon tectonic or sedimentary oversteepening. The sandy slump so generated passed sequentially into true fluxoturbidity and turbidity currents where the slope was steep enough, and if sufficient water was mixed in with the slurry. Thus the Chalky Island sequence provides direct field evidence in support of the widely accepted view that turbidity currents represent the end member of a gradational spectrum of subaqueous mass-transport processes (Shepard, 1951; Menard, 1960; Dott, 1963; Morgenstern, 1967).

Filling stage

The filling of submarine canyons that form part of a generally transgressive sedimentary regime presumably represents temporary periods during which supply and emplacement of sediment outstripped the process of basin-margin depression and canyon erosion. Hence the fill will have 'prograded' out from a more proximal canyon environment to the position in the fan-valley axis where it is now found. Only by such an interpretation can we explain the juxtaposition, at the same level, of channel-axis facies and levee turbidites (deposited from turbidity currents that must have derived from similar facies further up-channel). For the Sealers Bay fan-channels, thick deposits of creeping and slumping sands and breccia sands were built up, in some cases possibly right to the channel rim, as filling proceeded. Headward incision of the whole canyon complex probably continued right up to and into this stage, as evidenced by the thick-bedded fluxoturbidites that sometimes complete the cycle of sedimentation within a channel, and yet must have been derived from further upslope. When a channel was filled the locus of downslope movement of sediment shifted to a laterally adjacent channel, and levee turbidites overspilling from the new channel may or may not cap the older channel fill sequence (cf. Normark & Piper, 1969).

CONCLUSIONS AND SUMMARY

(1) Balleny Group represents continental margin shelf-canyon-fan environments of deposition. Sedimentation was initiated in response to local Oligocene tectonism.

(2) The mechanism of incision of the Chalky Island canyons was a sedimentational rather than a tectonic or eustatic event. In this particular case, canyon incision was probably produced by erosive debris-flows crossing and cutting into a narrow sandy shoreline sediment wedge adjacent to a relatively uplifting continental block.

(3) Canyon-fill sediments are represented by breccia-conglomerates and breccia-sands of Nuggets and possibly lower Sealers Formations. These sediments were almost entirely laid down by various types of inertia flow and slump-creep. The major sedimentary processes active in the proximal canyon environments on Chalky Island were therefore forms of mass-transport other than turbidity currents.

(4) A major channel developed within breccia-sands and fluxoturbidites of Sealers Formation is interpreted as an incised channel within a proximal fan-valley. The fill of the Sealers Bay Channel prograded out from more proximal canyon-fan environments, and its emplacement probably took place largely by slump-creep.

(5) Balleny Group represents a transgressive sedimentary sequence. The broadly successive superposition of slump-creep deposits + flowites—fluxoturbidites + levee deposits—proximal turbidites—distal turbidites therefore provides a field illustration of the hypothetical sequence of mass-transport processes thought to lead to the generation of turbidity currents.

ACKNOWLEDGMENTS

Access to Chalky Island was provided by Otago University's marine research vessel Munida; we are especially grateful to Associate-Professor E. J. Batham for making Munida available for this trip, and to skipper W. L. Tubman and crewmember T. Duval-Smith for their cheerful help. The field work was financially supported by New Zealand University Grants Committee research funds. The draft manuscript benefited greatly from critical comments made by Drs D. G. Bishop, P. D. Komar, C. A. Landis, E. Mutti, R. J. Norris, D. J. W. Piper and J. H. McD. Whitaker and we are most grateful to these colleagues for their advice and encouragement. The paper was completed whilst the senior author was on study leave, and he gratefully acknowledges the financial help of the Nuffield Foundation and the hospitality of the Oxford University Geology Department.

REFERENCES

BAGNOLD, R.A. (1954) Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. *Proc. R. Soc. Lond.* **A225**, 49–63.

BALLANCE, P.F. (1974) An inter-arc flysch basin in northern New Zealand: Waitemata Group (Upper Oligocene to Lower Miocene). *J. Geol.* **82**, 439–471.

CARTER, R.M. (1975) A summary discussion of subaqueous mass transport with particular respect to grain-flows and fluxoturbidites. *Earth Sci. Rev.* **11**.

CARTER, R.M. & LINDQVIST, J.K. (1975) Balleny Group, Chalky Island, Southern New Zealand: an inferred Oligocene submarine canyon and fan. *Pacif. Geol.* in press.

CARTER, R.M., LANDIS, C.A., NORRIS, R.J. & BISHOP, D.G. (1974) Suggestions towards a high-level nomenclature for New Zealand rocks. *J.R. Soc. N.Z.* **4,** 5–18.

CARTER, R.M. & NORRIS, R.J. (in prep.) The geology of the Blackmount area, Western Southland.

CHAMBERLAIN, T.K. (1964) Mass transport of sediment in the heads of Scripps Submarine Canyon, California. In: *Papers in Marine Geology* (Ed. by R. L. Miller), pp. 42–64. Macmillan, New York.

DILL, R.F. (1964) Sedimentation and erosion in Scripps Submarine Canyon Head. In: *Papers in Marine Geology* (Ed. by R. L. Miller), pp. 23–41. Macmillan, New York.

DOTT, R. H. (1963) Dynamics of subaqueous gravity depositional processes. *Bull. Am. Ass. Petrol. Geol.* **47,** 104–128.

DZULYNSKI, S., KSIAZKIEWICZ, M. & KUENEN, P.H. (1959) Turbidites in flysch of the Polish Carpathian Mountains. *Bull. geol. Soc. Am.* **70,** 1089–1118.

DZULYNSKI, S. & SANDERS, J.E. (1962) Current marks on firm mud bottoms. *Trans. Conn. Acad. Arts Sci.* **42,** 57–96.

GREGORY, M.R. (1969) Sedimentary structures and penecontemporaneous slumping in the Waitemata Group, Whangaparoa Peninsula, North Auckland, New Zealand. *N.Z. J. Geol. Geophys.* **12,** 248–282.

HALL, B.A. & STANLEY, D.J. (1973) Levee-bounded submarine base-of-slope channels in the Lower Devonian Seboomook Formation, Northern Maine. *Bull. geol. Soc. Am.* **84,** 2101–2110.

HAMPTON, M.A. (1972) The role of subaqueous debris flow in generating turbidity currents. *J. sedim. Petrol.* **42,** 775–793.

HEEZEN, B.C. & HOLLISTER, C.D. (1971) *The Face of the Deep*, pp. 659. Oxford University Press, Oxford.

HSU, K.J. (1959) Flute- and groove-casts in the Prealpine Flysch, Switzerland. *Am. J. Sci.* **257,** 529–536.

JACKA, A.D., BECK, R.H,. GERMAN., L.C.ST. & HARRISON, S.C. (1968) Permian deep-sea fans of the Delaware Mountain Group (Guadalupian), Delaware Basin. In: *Guadalupe facies, Apache Mountain area, West Texas. Soc. Econ. Paleont. Miner. (Permian Basin Section), Symposium guide book*, Publ. 68-11, pp. 49–90.

KELLING, G. & WOOLLANDS, M.A. (1969) The stratigraphy and sedimentation of the Llandoverian rocks of the Rhayader District. In: *The Pre-Cambrian and Lower Palaeozoic Rocks of Wales* (Ed. by A. Wood), pp. 255–282. University of Wales, Cardiff.

KUENEN, P.H. (1951) Properties of turbidity currents of high density. In: *Turbidity currents and the transportation of coarse sediments to deep water* (Ed. by J. L. Hough). *Spec. Publ. Soc. Econ. Paleont. Miner., Tulsa,* **2,** 14–33.

KUENEN, P.H. (1958) Problems concerning source and transportation of flysch sediments. *Geol. Mijnb.* **20,** 329–339.

LOWE, D.R. (1972) Submarine canyon and slope channel sedimentation model as inferred from Upper Cretaceous deposits, Western California. *Proc. 24th Int. geol. Congr. (Montreal), Sect. 6,* 75–81.

MENARD, H.W. (1960) Possible pre-Pleistocene deep-sea fans off central California. *Bull. geol. Soc. Am.* **71,** 1271–1278.

MIDDLETON, G.V. (1967) Experiments on density and turbidity currents. III. Deposition of sediment. *Can. J. Earth Sci.* **4,** 475–505.

MIDDLETON, G.V. (1970) Experimental studies related to problems of flysch sedimentation. In: *Flysch Sedimentology in North America* (Ed. by J. Lajoie). *Spec. Pap. geol. Ass. Can.* **7,** 253–272.

MIDDLETON, G.V. & HAMPTON, M.A. (1973) Part 1: Sediment gravity flows—mechanics of flow and deposition. In: *Turbidites and deep-water sedimentation. Soc. Econ. Paleont. Miner. Pacific Sect., Short-Course Lecture Notes,* pp. 1–38.

MORGENSTERN, H.R. (1967) Submarine slumping and the initiation of turbidity currents. In: *Marine Geotechnique* (Ed. by A. F. Richards), pp. 189–220. University of Illinois, Urbana.

MUTTI, E. (1974) Examples of ancient deep-sea fan deposits from Circum-Mediterranean geosynclines. In: *Modern and ancient geosynclinal sedimentation* (Ed. by R. H. Dott and R. H. Shaver). *Spec. Publ. Soc. Econ. Paleont. Miner., Tulsa,* **19,** 92–105.

NELSON, C.H. & NILSEN, T.H. (1974) Depositional trends of modern and ancient deep-sea fans. In: *Modern and ancient geosynclinal sedimentation* (Ed. by R. H. Dott and R. H. Shaver). *Spec. Publ. Soc. Econ. Paleont. Miner., Tulsa,* **19,** 69–91.

NORMARK, W.R. (1970) Growth patterns of deep-sea fans. *Bull. Am. Ass. Petrol. Geol.* **54,** 2170–2195.

NORMARK, W.R. (1974) Submarine canyons and fan valleys: factors affecting growth patterns of deep-sea fans. In: *Modern and ancient geosynclinal sedimentation* (Ed. by R. H. Dott and R. H. Shaver). *Spec. Publ. Soc. Econ. Paleont. Miner., Tulsa,* **19,** 56–68.

NORMARK, W.R. & PIPER, D.J.W. (1969) Deep-sea fan-valleys, past and present. *Bull. geol. Soc. Am.* **80,** 1859–1866.

PIPER, D.J.W. & NORMARK, W.R. (1971) Re-examination of a Miocene deep-sea fan and fan-valley, southern California. *Bull. geol. Soc. Am.* **82,** 1823–1830.

REIMNITZ, E. (1971) Surf-beat origin for pulsating bottom currents in the Rio Balsas Submarine Canyon, Mexico. *Bull. geol. Soc. Am.* **82,** 81–90.

REIMNITZ, E. & GUTIERREZ-ESTRADA, M. (1970) Rapid change in the head of the Rio Balsas Submarine canyon system. *Mar. Geol.* **8,** 245–258.

SANDERS, J.E. (1965) Primary sedimentary structures formed by turbidity currents and related resedimentation mechanisms. In: *Primary sedimentary structures and their hydrodynamic interpretation* (Ed. by G. V. Middleton). *Spec. Publ. Soc. Econ. Paleont. Miner., Tulsa,* **12,** 192–217.

SCHOLL, D.W., BUFFINGTON, E.C., HOPKINS, D.M. & ALPHA, T.R. (1970) The structure and origin of the large submarine canyons of the Bering Sea. *Mar. Geol.* **8,** 187–210.

SHEPARD, F.P. (1951) Mass movements in submarine canyon heads. *Trans. Am. Geophys. Union,* **32,** 405–418.

SHEPARD, F.P. & DILL, R.F. (1966) *Submarine Canyons and Other Sea Valleys,* pp. 381. Rand McNally, Chicago.

SHEPARD, F.P., DILL, R.F. & VON RAD, U. (1969) Physiography and sedimentary processes of La Jolla submarine fan and fan-valley, California. *Bull. Am. Ass. Petrol. Geol.* **53,** 390–420.

STANLEY, D.J. (1967) Comparing patterns of sedimentation in some modern and ancient submarine canyons. *Earth Planet. Sci. Letts,* **3,** 371–380.

STANLEY, D.J. (1971) Bioturbation and sediment failure in some submarine canyons. *Vie milieu,* Suppl. 22, 541–555.

STANLEY, D.J. & UNRUG, R. (1972) Submarine channel deposits, fluxoturbidites and other indicators of slope and base-of-slope environments in modern and ancient marine basins. *Spec. Publ. Soc. Econ. Paleont. Miner., Tulsa,* **16,** 287–340.

STANLEY, D.J. & BOUMA, A.H. (1964) Methodology and paleogeographic interpretation of flysch formations: a summary of studies in the Maritime Alps. In: *Turbidites* (Ed. by A. H. Bouma and A. Brouwer), pp. 34–64. *Developments in Sedimentology,* **3.** Elsevier, Amsterdam.

STAUFFER, P.H. (1967) Grain-flow deposits and their implications, Santa Ynez Mountains, California. *J. sedim. Petrol.* **37,** 487–508.

STETSON, H.C. & SMITH, J.F. (1938) Behaviour of suspension currents and mud slides on the continental slope. *Am. J. Sci.* **35,** 1–13.

WALKER, R.G. (1966) Deep channels in turbidite-bearing formations. *Bull. Am. Ass. Petrol. Geol.* **50,** 1899–1917.

WALKER, R.G. (1967) Turbidite sedimentary structures and their relationship to proximal and distal depositional environments. *J. sedim. Petrol.* **37,** 25–43.

WALKER, R.G. & MUTTI, E. (1973) Part IV. Turbidite facies and facies associations. In: *Turbidites and deep-water sedimentation. Soc. Econ. Paleont. Miner., Pacific Sect., Short-Course Lecture Notes,* pp. 119–157.

WALKER, R.G. & PETTIJOHN, F.J. (1971) Archaean sedimentation: analysis of the Minnitaki Basin, northwestern Ontario, Canada. *Bull. geol. Soc. Am.* **82,** 2099–2130.

WOOD, B.L. (1960) *Sheet 2 Fiord (1st Edition), Geological map of New Zealand,* 1 : 250,000. N.Z. D.S.I.R., Wellington.

WOOD, B.L. (1966) *Sheet 24 Invercargill (1st Edition), Geological Map of New Zealand,* 1: 250,000. N.Z. D.S.I.R., Wellington.

WHITAKER, J.H.McD. (1962) The geology of the area around Leintwardine, Herefordshire. *Q. Jl geol. Soc. Lond.* **118,** 319–351.

WHITAKER, J.D.McD. (1974) Ancient submarine canyons and fan valleys. In: *Modern and ancient geosynclinal sedimentation* (Ed. by R. H. Dott and R. H. Shaver). *Spec. Publ. Soc. Econ. Paleont. Miner., Tulsa,* **19,** 106–125.

(*Manuscript received* 27 *August* 1974)