Paper VI

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Turbidites in the Upper Carboniferous Ross Formation, western Ireland: reconstruction of a channel and spillover system

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ABSTRACT

The Upper Carboniferous deep-water rocks of the Shannon Group were deposited in the extensional Shannon Basin of County Clare in western Ireland and are superbly exposed in sea cliffs along the Shannon estuary. Carboniferous limestone floors the basin, and the basin-fill succession begins with the deep-water Clare Shales. These shales are overlain by various turbidite facies of the Ross Formation (460 m thick). The type of turbidite system, scale of turbidite sandstone bodies and the overall character of the stratigraphic succession make the Ross Formation well suited as an analogue for sand-rich turbidite plays in passive margin basins around the world. The lower 170 m of the Ross Formation contains tabular turbidites with no channels, with an overall tendency to become sandier upwards, although there are no small-scale thickening- or thinning-upward successions. The upper 290 m of the Ross Formation consists of turbidites, commonly arranged in thickening-upward packages, and amalgamated turbidites that form channel fills that are individually up to 10 m thick. A few of the upper Ross channels have an initial lateral accretion phase with interbedded sandstone and mudstone deposits and a subsequent vertical aggradation phase with thick-bedded amalgamated turbidites. This paper proposes that, as the channels filled, more and more turbidites spilled further and further overbank. Superb outcrops show that thickening-upward packages developed when channels initially spilled muds and thin-bedded turbidites up to 1 km overbank, followed by thick-bedded amalgamated turbidites that spilled close to the channel margins. The palaeocurrent directions associated with the amalgamated channel fills suggest a low channel sinuosity. Stacks of channels and spillover packages 25–40 m thick may show significant palaeocurrent variability at the same stratigraphic interval but at different locations. This suggests that individual channels and spillover packages were stacked into channel-spillover belts, and that the belts also followed a sinuous pattern. Reservoir elements of the Ross system include tabular turbidites, channel-fill deposits, thickening-upward packages that formed as spillover lobes and, on a larger scale, sinuous channel belts 2·5–5 km wide. The edges of the belts can be roughly defined where well-packaged spillover deposits pass laterally into muddier, poorly packaged tabular turbidites. The low-sinuosity channel belts are interpreted to pass downstream into unchannellized tabular turbidites, equivalent to lower Ross Formation facies.

Keywords Ireland, Ross Formation, spillover lobes, turbidites, turbidite channels.

INTRODUCTION

Deep-water reservoir rocks dominate and are becoming increasingly important in exploration and production in most Atlantic basins such as offshore western Europe, along the West African margin, on the east margin of South America and in the Gulf of Mexico. Many of these deep-water systems are well studied using high-quality three-dimensional seismic and well data, but detailed outcrop data of such systems are important, especially in the understanding of subseismic-scale sandbody type and geometries. The genetic link between the reservoir elements in complex deep-water systems is also vital in reservoir modelling and in the understanding of reservoir flow and production.

The Upper Carboniferous deep-water rocks of the Ross Formation in County Clare, western Ireland, are superbly exposed in sea cliffs along the Shannon estuary and Atlantic coast (Fig. 1). The type of turbidite system, scale of turbidite sandstone bodies and overall character of the stratigraphic succession make the Ross Formation well suited as an analogue for sand-rich turbidite plays in passive margin basins around the world.

In sea cliffs around the coast of County Clare and on the south side of the Shannon estuary at Ballybunion (Fig. 1), continuous unbroken vertical sections up to >460 m thick can be observed in detail and, in places, beds can be walked laterally for over 1 km. Both sheet-like and channellized turbidites are present, as well as spectacular slump and slide horizons. Channel stacking occurs in several places, and the transitions from channellized to sheet-like geometries can be observed at channel margins. Folding makes the soles of the beds easily accessible for palaeocurrent measurement, and relationships of palaeocurrents to the facies and stratigraphic development can be analysed.

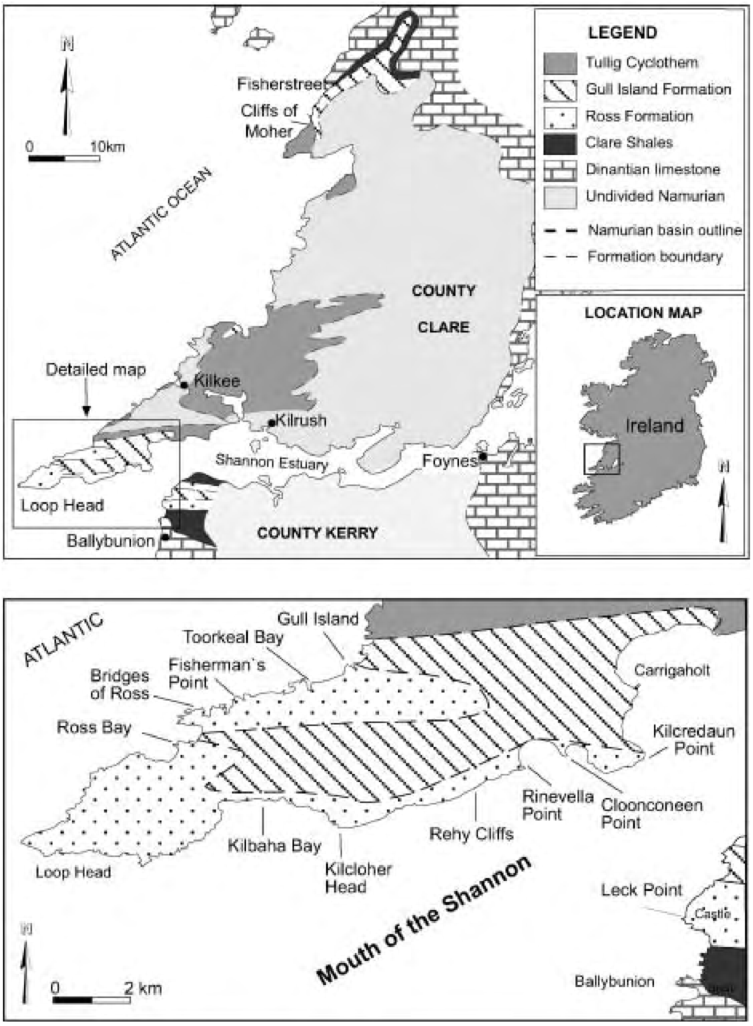


Fig. 1. Location map of Ireland, with rectangle showing enlarged area of County Clare. Map below shows the Loop Head Peninsula and Ballybunion areas. All areas mentioned in the text are shown.

The purpose of this paper is to present both an overall vertical and lateral stratigraphic development, reconstruction of depositional environments and processes, as well as detailed studies of the reservoir elements of the Ross Formation. The paper integrates the various outcrop data into a reconstruction of the basin at the time of turbidite deposition. Emphasis will be placed on the geometric forms of the various facies and sandbodies that may be analogous to deep-water reservoir elements in the subsurface. These data will enhance the understanding of how such turbidite systems evolve and the genetic relationship between the different sandbodies.

STRATIGRAPHY

The stratigraphy of the Namurian section (Fig. 2) relies on biostratigraphy that is based on goniatite-bearing marine bands, as determined by Hodson (1954a,b), Hodson & Lewarne (1961) and Collinson *et al.* (1991). The lithostratigraphy was proposed by Rider (1974) and, in the Shannon estuary area, the Shannon Group consists of the Clare Shales (180 m), overlain by the Ross Formation and the Gull Island Formation. The maximum thickness of the Ross Formation is estimated here to be ≈460 m, contrasting with previous estimates of the order of 380 m (e.g. Collinson *et al.*, 1991; Elliott, 2000a,b). The overlying Gull Island Formation is about 550 m thick. Northward (north Clare, Fig. 2), the Clare Shales thin dramatically to about 10 m, the Ross Formation is condensed into a very thin succession of shales, and the Gull Island Formation thins to about 130 m.

The Shannon Group is a basin-filling succession, with the Clare Shales representing monotonous deep-water deposition. The overlying Ross Formation contains sheet-like and channellized turbidites, with three major slump and slide horizons. The overlying Gull Island Formation is characterized by slumps and slides, with some turbidites in the lower part of the formation (Martinsen, 1989). After the basin filled, five shallow-water to non-marine cyclothems developed (Rider, 1974; Central Clare Group, Fig. 2).

The base of the Ross Formation is exposed at Ballybunion and is taken at the first sandstone bed above the Clare Shales. This first bed occurs just south of the large waterfall of Glenachoor Stream, about 3·3 km north of the castle in Ballybunion. No single lithological criterion can be used to separate the Ross Formation from the overlying Gull Island Formation. The Ross Formation is sandier than the Gull Island Formation and is dominated by turbidite deposits, with only three main slump/slide horizons. The Gull Island Formation also contains some turbidites, but is muddier than the Ross Formation and is dominated by slump/slide horizons. The top of the Ross Formation is taken at the *R. dubium* marine band (Collinson *et al.*, 1991). In the Loop Head Peninsula (Fig. 1), the *R. dubium* and *R. paucicrenulatum* marine bands occur < 1 m apart, whereas at

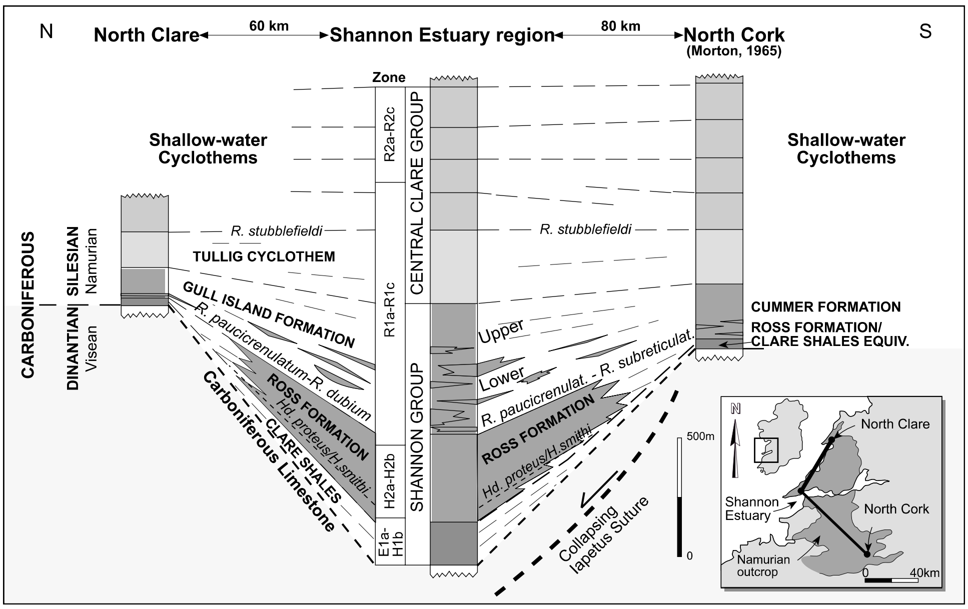


Fig. 2. Stratigraphy of the Clare Basin and adjacent areas. See text for details in the Shannon estuary region.

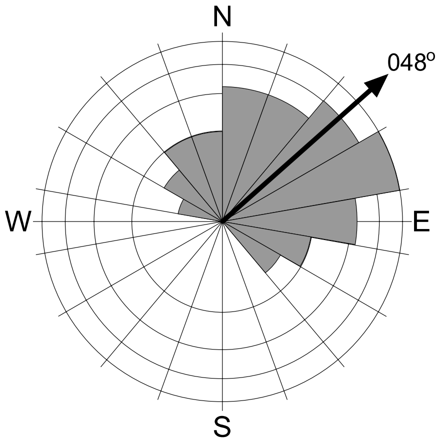


Fig. 3. Ross Formation palaeoflow, summarizing readings taken from 603 beds. Data are grouped into 20° classes. The grand vector mean is 048°.

Ballybunion, they are separated by up to 70 m of sandstones and mudstones.

In County Clare, the general dispersal pattern of the Ross Formation is indicated by palaeoflow readings taken from 603 beds. The grand vector mean of 048° (Fig. 3) is an areally and stratigraphically averaged direction. All the local palaeoflow directions presented in this paper should be evaluated in the context of a general north-eastward dispersal.

Subdivision of the Ross Formation

This paper informally divides the Ross Formation into a lower and upper part. The lower Ross Formation is only exposed at Ballybunion (and possibly at Foynes Island; Hodson & Lewarne, 1961). The lower Ross Formation is about 170 m thick and is characterized by tabular, non-channellized turbidites, with only one thin slumped horizon near the base. There is no interpreted well-developed packaging of the turbidites into thickening- or thinning-upward successions. The contact with the upper Ross Formation is taken at the base of thicker amalgamated beds (see Fig. 4). The upper Ross Formation crops out around the Loop Peninsula, is about 290 m thick and contains sheet-like and channellized turbidites, as well as at least three major slump/slide horizons (Fig. 4). Packaging of the turbidites into 2–5 m thickening-upward successions is common.

PREVIOUS WORK

Hodson (1954a,b) and Hodson & Lewarne (1961) established the biostratigraphy in northern County Clare. The first sedimentological work by Gill & Kuenen (1958), who described the spectacular sand volcanoes that occur on top of many of the slumped horizons, was expanded by Gill (1979). The present lithostratigraphy (Fig. 2) was set up by Rider (1974), who established the deep-water origin of the Clare Shales and the turbidite origin of the Ross Formation. He noted that the palaeocurrents showed a 'definitely south-westerly origin' for the turbidity currents.

More detailed work on the Ross and Gull Island Formations was undertaken by Bakken (1987), Kloster (1987), Martinsen (1987, 1989), Martinsen & Bakken (1990) and summarized by Collinson *et al.* (1991). These papers suggested that the majority of the slump and slide horizons in the Gull Island Formation had moved south-eastward into the basin, with turbidity currents flowing north-easterly along the axis of the basin. The Ross turbidites were regarded as basin-floor deposits, and the Gull Island slumps and slides were interpreted as a prograding slope. The Ross Slide, recently described by Strachan (2002), occurs in the upper part of the Ross Formation and flowed north-eastward along the basin axis. The Clare basin appears to have developed as a result of extension and collapse above the position of the former Iapetus Suture, as discussed by Collinson *et al.* (1991), Wignall & Best (2000) and Martinsen *et al.* (2000).

Chapin *et al.* (1994) suggested that the Ross Formation represents an aggradational, sand-rich fan within a rapidly subsiding basin, with small, coalescing mid–outer fan lobes with multiple shallow channels (Chapin *et al.*, 1994, p. 53). They noted that the distribution of bed thickness in vertical profile is mostly random; small-scale thinning- and thickening-upward trends within

Fig. 4. Measured sections of the Ross Formation. Locations shown on inset map, lower left. Datum is taken as the *R. dubium* marine band, which is also the boundary of the Ross and Gull Island Formations. Note that the complete Ballybunion section occupies two columns, with the lower/upper Ross boundary in the right-hand column. Scale is shown on the left, with individual ticks on sections 5 m apart. Note also that the horizontal scale on the sections represents bed thickness, not grain size (which is a very uniform fine sand). Shaded areas show correlation of slump/slide horizons.

sets of 5–20 beds were occasionally observed within sheet sandstones. Also, sheet sandstones were described as being stacked in a vertically disorganized fashion (i.e. neither fining/thinning up nor coarsening/thickening up). Chapin *et al.* (1994, p. 62) described megaflutes and interpreted them as the result of increased turbulence associated with hydraulic jumps near channel-lobe transitions. Most lobe deposits interpreted in the literature show thickening-upward successions (Mutti & Ghibaudo, 1972; Mutti & Ricci Lucchi, 1972), but these were only occasionally observed in the Ross Formation by Chapin *et al.* (1994). Nevertheless, Chapin *et al.* (1994, p. 67) suggested that small, ephemeral lobes were fed from shallow channels that often switched position.

More recently, descriptions of the Ross Formation have been given by Elliott (2000a,b) discussing megaflute erosion surfaces and the channelized turbidite system. Elliott (2000a) noted that alternations of thin- and thick-bedded intervals occurred in the sheet-like turbidite elements, and that these could be viewed as small-scale thickening-upward packages deposited beyond the downcurrent limits of channels, possibly as turbidite lobes.

MEASURED SECTIONS AND CORRELATIONS

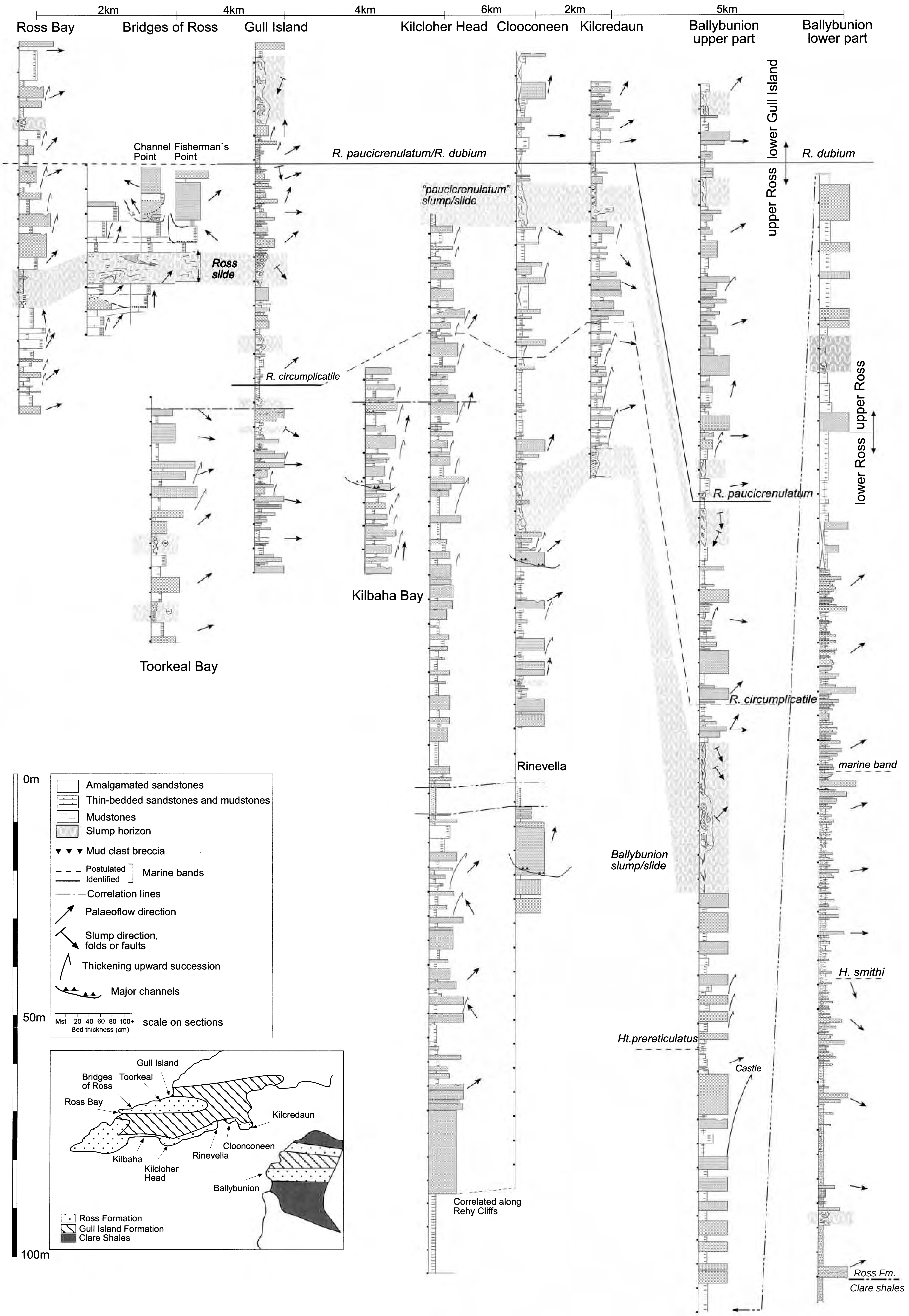
Detailed sections (Fig. 4) were measured with bed-by-bed logging on the north side of the Loop Peninsula at Ross Bay (south side), Bridges of Ross, Toorkeal Bay and near Gull Island (Fig. 1). On the south side of the Loop Peninsula, sections were measured at Kilbaha Bay, Kilcloher Head, Rinevella Point, Cloonconeen Point and Kilcredaun Point. A complete section of the Ross Formation was measured on the south side of the Shannon estuary at Ballybunion (Fig. 1). The *R. dubium* marine band was used as datum in the correlation diagram (Fig. 4) for the sections at Gull Island, Cloonconeen Point, Kilcredaun Point and Ballybunion. The sections at Ross Bay and Bridges of Ross can be correlated with Gull Island using the position of the Ross Slide. The section at Rinevella Point has been correlated with the sections at Cloonconeen Point and Kilcloher Head as suggested by Kloster (1987). The Kilcloher–Rinevella correlation is supported by the presence of an undeformed mudstone layer almost 5 m thick in both sections; this can be seen about 100 m above the base of the Kilcloher section (Fig. 4). Thus, the Rinevella section has been placed just below the Cloonconeen section, and they are presented as one composite section in Fig. 4.

The Kilcloher Head section occurs below the *R. dubium* and *R. paucicrenulatum* marine bands. The accessible measured section has been extended downwards into a thick interval of thin-bedded sandstones and mudstones by observation of the cliffs from a boat (lowest 15 m of the Kilcloher section in Fig. 4). This interval can be traced along the Rehy Cliffs (Fig. 1, observations from a boat) and occupies a position estimated to be about 50 m below the channel at Rinevella Point. The Kilbaha Bay section can be correlated precisely with the Kilcloher Head section by structural mapping and section measurement in the eastern part of Kilbaha Bay. The section at Toorkeal Bay is the most difficult to place. It is suggested here that it belongs immediately below the uppermost slump/slide in the Gull Island section (Fig. 4), but otherwise as high as possible stratigraphically. In this way, the two slump/slide horizons at Toorkeal are not positioned much lower than the other slump/slide horizons in the upper Ross Formation.

Where accessible, the sections were measured at the scale of individual beds, noting sandstone and mudstone thicknesses, internal sedimentary structures and palaeocurrent directions. Where sections cropped out in inaccessible cliffs (parts of Ballybunion and Gull Island), thicknesses were measured by tape on the cliff top and corrected for local dip. Generalized descriptions of inaccessible sections were made using binoculars from the cliff top and from photomosaics of the cliff taken from a small boat. At Ballybunion, about 180 m of the total (460 m) was measured on the cliff top.

LOWER ROSS FORMATION

The lowermost Ross Formation is only well exposed at Ballybunion. It is estimated to be about 170 m thick, and the lowest 145 m is superbly and continuously exposed in the cliffs and on the wave-cut platform. The section consists of interbedded sandstones and mudstones, with a tabular, sheet-like bedding style and no indications of channelling (Fig. 5). The sandstone and mudstone beds do not have any significant changes in geometry or thickness across the ≈ 300 m width of outcrop. The average sandstone bed is 0·14 m thick, the thickest individual bed is



2km
4km
4km
6km
2km
5km
Ross Bay
Bridges of Ross
Gull Island
Kilcloher Head
Clooconeen
Kilcredaun
Ballybunion upper part
Ballybunion lower part
lower Gull Island
upper Ross
lower Ross
Channel Point
Fisherman`s Point
R. paucicrenulatum/R. dubium
R. dubium
"paucicrenulatum" slump/slide
Ross slide
R. circumplicatile
Kilbaha Bay
Toorkeal Bay
R. paucicrenulatum
R. circumplicatile
Rinevella
marine band
Ballybunion slump/slide
H. smithi
Ht.prereticulatus
Castle
Correlated along Rehy Cliffs
Ross Fm.
Clare shales
0m
50m
100m
Amalgamated sandstones
Thin-bedded sandstones and mudstones
Mudstones
Slump horizon
Mud clast breccia
Postulated
Identified
Marine bands
Correlation lines
Palaeoflow direction
Slump direction, folds or faults
Thickening upward succession
Major channels
Mst 20 40 60 80 100+
Bed thickness (cm)
scale on sections
Gull Island
Bridges of Ross
Toorkeal
Ross Bay
Kilcredaun
Clooconeen
Rinevella
Kilbaha
Kilcloher Head
Ballybunion
Ross Formation
Gull Island Formation
Clare Shales

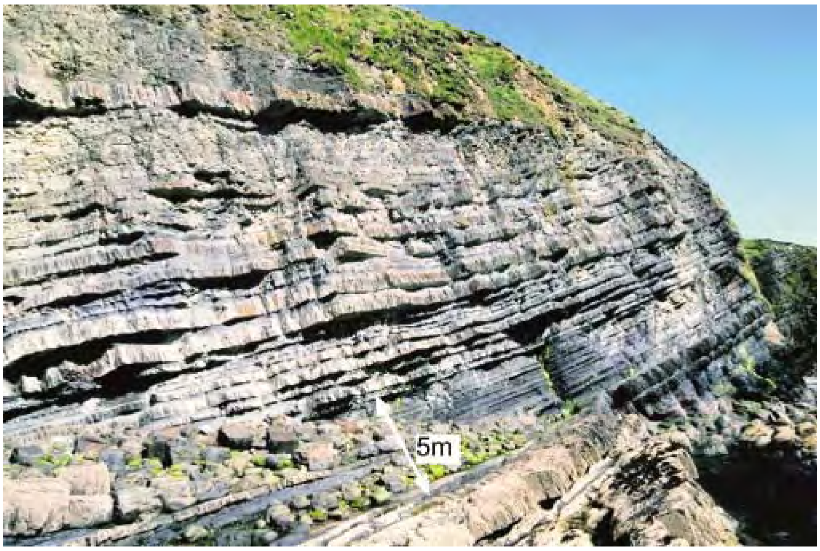


Fig. 5. Tabular turbidites at Ballybunion. Photo shows section from about 38 to 53 m (Fig. 4).

1·27 m, and the thickest amalgamated bed consists of three individual beds with a total thickness of 1·74 m. Most beds are structureless (Bouma A division), with only about 10% showing Bouma B and/or C divisions.

The lowest 35 m of section consists mostly of mudstone (Fig. 4). There is a general tendency for more amalgamated beds to occur stratigraphically higher in the section, giving an overall sandier-upward nature to the lower Ross Formation. Nevertheless, there are also some apparently random occurrences of thicker beds (up to almost 1 m) in the lower part of the section. No convincing trends of bed thickness (e.g. thickening-upward successions) on the scale of a few metres are observed or interpreted. This is a major contrast with the upper Ross Formation, which is characterized by such successions, on a 2–5 m scale. The lower Ross Formation contains only one thin slumped horizon about 10 m above the base.

Lower Ross Formation palaeoflow

Flow directions were measured in 91 beds at Ballybunion, using flutes, rill marks, grooves, prods and other miscellaneous tool marks. Flow directions were first plotted against stratigraphic height (Fig. 6A). The data (Fig. 6A) suggest a gradual shift from flows directed towards 060° to flows towards 180° in the lower 60 m of section. Above that, there is then a sudden shift to flows towards 100° and a gradual overall change towards about 040° through the section from 65 m to 145 m. The sudden shift at about 60 m coincides with concretionary dark shale interpreted as the *H. smithi* marine band. The palaeoflows from below and above the black shale could be interpreted to form two distinct data sets, and the data in each set were smoothed using a three-bed moving average of the palaeoflow directions. The vector mean of the three beds was plotted against the stratigraphic height of the middle bed of the three, and the trends are highlighted by arrows in Fig. 6B. Examination of the smoothed trends (Fig. 6B) suggests smaller scale trends, shown by arrows in Fig. 6C. Between 67 and 87 m, flows consistently swing from about 090° to 060° and, between 88 and 115 m, flows swing from about 090° to 040°. The data between 115 and 145 m are more random. Interpretations of these trends will be presented later.

UPPER ROSS FORMATION

The upper Ross Formation has an overall thickness of about 290 m and is characterized by thickening-upward packages of turbidites, poorly packaged turbidites, channels and slump/slide horizons. Sections were measured at Bridges of Ross (35 m), the south side of Ross Bay (79 m), Toorkeal Bay (47 m), near Gull Island (84 m), Cloonconeen Point (117 m), Rinevella Point (27 m), Kilbaha Bay (42 m), Kilcredaun Point (82 m) and at Kilcloher Head (including part of Rehy Cliff, with thicknesses estimated from a photomosaic and totalling about 224 m). The upper Ross Formation was also measured at Ballybunion (290 m), where it is continuously exposed, but partly in inaccessible cliffs.

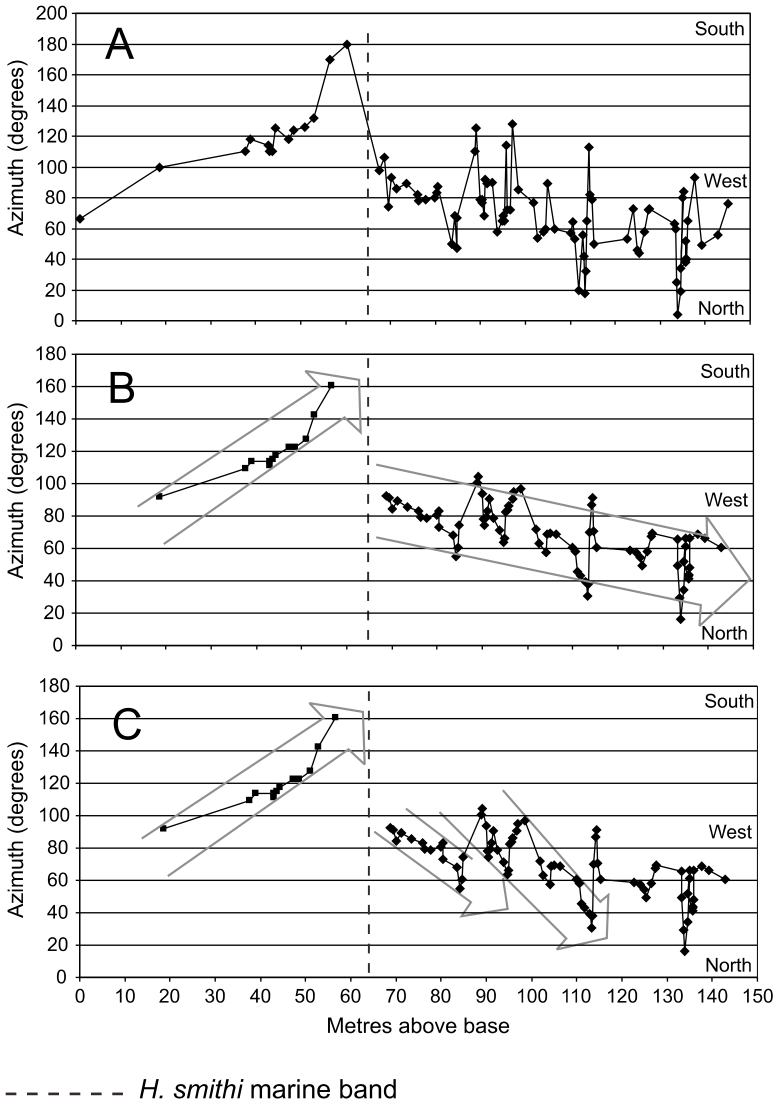


Fig. 6. Palaeoflow at Ballybunion. (A) Raw data (91 palaeoflow measurements) plotted against stratigraphic position of the observation. (B) Three-bed moving average of the raw data shown in (A). The data below 65 m were included in one moving average, and the data above 65 m were included in a separate moving average. Background arrows suggest possible long-term trends in the data. The apparent break between the two trends appears to coincide with the position of the *H. smithi* marine band. (C) The same three-bed moving averages as in (B), but arrows show the possible interpretation of three trends rather than the two shown in (B).

Upper Ross Formation thickening-upward packages

Parts of the upper Ross Formation are characterized by packaging of turbidites into thickening-upward successions. Other parts can be termed poorly packaged or unpackaged and are discussed later. Where the packages are well developed (e.g. Kilbaha Bay, Ross Bay), they contain four parts (Figs 7 and 8):

(4) (top) an upper surface characterized by megaflutes (Fig. 8);
(3) thick-bedded amalgamated turbidites;
(2) thin-bedded turbidites;
(1) (base) grey mudstones with thin silty laminations.

Successive thickening-upward packages commonly occur, this being best seen at Kilbaha Bay, Ross Bay and Kilcloher Head (Fig. 7). More poorly developed package successions are exposed in all the other upper Ross sections (Fig. 4). The average thickness of 165 packages is 2·13 m (range 0·44–7·42 m). Packaging has been discussed, but underemphasized by previous authors (Collinson *et al*., 1991; Elliott, 2000a). The present paper will show that thickening-upward packages are commonly associated with channels, and are frequently linked with, and capped by, megaflute erosion surfaces.

Basal mudstones

Basal mudstones do not occur in every package. They commonly overlie megaflute surfaces (Fig. 8) and drape the sides of the megaflutes. Very thin-bedded turbidites on a centimetre scale may be interbedded with the mudstones

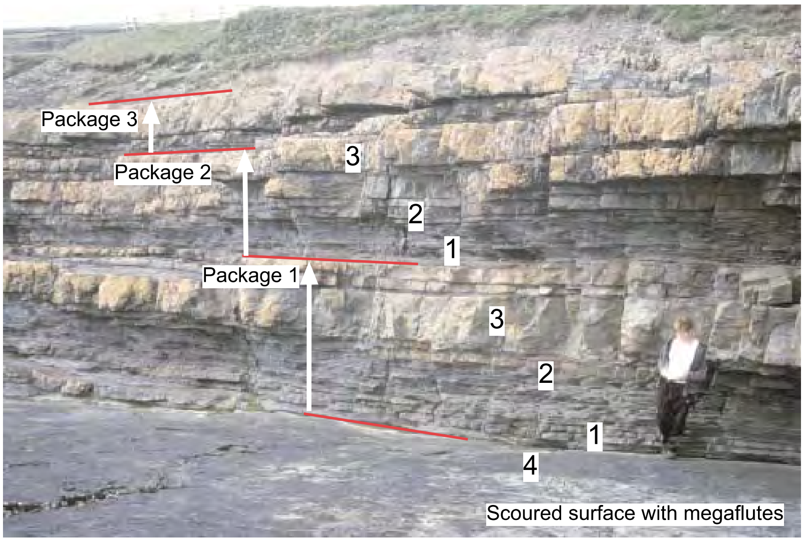


Fig. 7. Sandier and thickening-upward packages at Kilcloher Head, about 30 m below the interpreted position of the *R. circumplicatile* marine band (Fig. 4). There are no megaflutes in the photograph of the scoured surface in the foreground.

Fig. 8. Megaflute at Ross Bay, with 0·15 m scale in nose of flute. Fill begins with grey mudstones, followed by a few thin-bedded turbidites, capped by amalgamated sandstones. This succession constitutes a thickening-upward package.

and may also form part of the fill of the megaflutes, where they commonly onlap the margins of the flute. Where megaflutes are absent, the mudstones are flat-bedded, and the interbedded thin turbidites are very continuous (across outcrop, several 100 metres). At Kilbaha and Ross Bay, basal mudstones thicker than 0·1 m occur in about 50% (Kilbaha) to 70% (Ross Bay) of the packages, with the average thickness of the mudstones being 0·48 m (range 0·10–1·40 m). The thickest interval of mudstones (1·40 m) occurs at Ross Bay (45 m level in the measured section, Fig. 4), where they are black, very fine grained and lack silty laminations. This lithology is very similar to that of the marine bands in other locations.

Thin-bedded turbidites

Thin-bedded turbidites were measured in 126 packages (Table 1). Individual sandstone beds average 0·05 m thick, and the interbedded mudstones average 0·07 m (1468 beds measured, Table 2). Groups of thin-bedded turbidites average 1·15 m thick (range 0·10–4·20 m) in each of the 126 packages. Individual beds are variable in geometry: some are continuous across the outcrop, but others may pinch and swell and may disappear entirely across the width of an outcrop. Some of the thinner beds may be restricted to megaflute fills and may onlap the erosion surface adjacent to the megaflutes (Fig. 8). Small sole marks are common. Many beds begin with a Bouma A division and have thin single sets of ripple cross-lamination at their top (Bouma C division). Climbing ripples and convolute lamination are rare.

Thick-bedded amalgamated turbidites

The thick-bedded amalgamated turbidites are normally structureless (Bouma A division). Amal-

Table 1. Thicknesses of units of mudstones and thin-bedded turbidites, and units of amalgamated thick-bedded sandstones within 126 packages.

Sections	Thin-bedded turbidites and mudstones: average unit thickness (range) and no. of units	Amalgamated sandstones: average unit thickness (range) and no. of units
Kilcloher Head 0–60 m section	1·22 m (0·16–3·99 m): 24 units	1·45 m (0·26–5·21 m): 21 units
Kilcloher Head 167–219 m section	0·95 m (0·19–3·04 m): 24 units	1·22 m (0·30–2·73 m): 23 units
Toorkeal Bay 0–46·5 m section	2·11 m (0·65–4·03 m): 9 units	2·27 m (1·40–3·94 m): 9 units
Ross Bay 0–76·5 m section	1·73 m (0·60–4·20 m): 13 units	2·25 m (0·52–6·12 m): 14 units
Kilbaha 0–42 m section	0·73 m (0·10–2·16 m): 19 units	1·14 m (0·25–2·64 m): 20 units
Bridges of Ross 0–10·5 m section	0·69 m (0·20–1·28 m): 3 units	1·54 m (0·70–2·10 m): 5 units
Bridges of Ross 0–42 m section	1·11 m (0·18–2·42 m): 23 units	0·71 m (0·29–1·96 m): 22 units
Kilcredaun 65–82 m section	0·84 m (0·19–2·07 m): 11 units	0·48 m (0·23–0·60 m): 11 units
All data	1·15 m (0·10–4·20 m): 126 units	1·30 m (0·23–6·12 m): 125 units

Table 2. Average thickness of individual beds of packages.

	Thin-bedded turbidites and interbedded mudstone			Thick amalgamated sandstones			Sand percentage		
Sections	Sst. (m)	Mst. (m)	No. of beds	Sst. (m)	Mst. (m)	No. of beds	Thin %	Thick %	Total %
Ballybunion 0–145 m section				0·14					52
Kilcloher Head 0–60 m section	0·06	0·10	201	0·04	0·03	80	42	98	70
Toorkeal Bay 0–46·5 m section	0·06	0·05	207	0·31	0·01	57	44	84	61
Ross Bay 0–76·5 m section	0·06	0·07	149	0·21	0·01	142	45	99	57
Kilbaha 0–42 m section	0·05	0·03	435	0·31	Trace	287	65	99	84
Bridges of Ross 0–11 m section	0·04	0·03	28	0·18	0·03	28			
Bridges of Ross 17–42 m section	0·04	0·03	16	0·18	0·03	28	90	99	96
Kilcredaun 7–49 m section	0·04	0·07	318	0·20	0·03	75	53	97	70
Kilcredaun 65–82 m section	0·04	0·06	114	0·19	0·03	26	55	95	69
All data	0·05	0·07	1468	0·27	0·01	723	49	96	61

Sst. is sandstone, Mst. is mudstone. Right part of table shows sand percentages within the thin-bedded units (Thin), thick-bedded units (Thick) and total sand percentage from different localities. See Fig. 4 for reference to measured sections.

gamation surfaces are shown by horizontal gently scoured (Fig. 8) or loaded parting planes within beds. These surfaces are commonly cryptic and difficult to trace along the beds, making the identification of individual beds impossible in places. Elsewhere, the cryptic parting planes may become better defined and draped by millimetre-scale layers of mudstone or thin layers of mudstone clasts. Given the difficulties of defining individual beds, the estimated individual bed thickness is ≈0·27 m. Maximum thickness of individual beds may be as much as ≈2 m. The average thickness of amalgamated turbidites in a package is ≈1·30 m (range 0·23–6·12 m; 125 packages measured). Sole marks are most easily measured on the lowest surface of a group of amalgamated beds, but measurements can also be obtained where thin mudstone partings have weathered out within groups of beds. Flutes up to a few centimetres wide are more common on the bases of amalgamated beds than on thin-bedded turbidites.

Megaflutes and megaflute erosion surfaces

Megaflutes (Figs 8–10) have been described in previous publications (Elliott, 2000a,b). They are 1–40 m wide, several metres to at least 25 m long and up to about 3 m deep. They have the same morphology as normal sized flutes seen on the soles of sandstones but, in the Ross Formation, they are most easily observed on the weathered-out uppermost surfaces of packages (Figs 8 and 9). However, megaflutes can be found at any stratigraphic horizon within the upper amalgamated turbidites of a package (Fig. 10), and they also occur rarely within the thin-bedded turbidites. Within the packages, the megaflutes can normally only be observed in cross-section. One

Fig. 9. The 'classic' megaflute at Ross Bay, about 10 m below the *R. paucicrenulatum*/*R. dubium* marine bands (Fig. 4). Note that the sinuous crested ripples are eroded by the flute, and that the ripples do not descend into the flute itself, which has smooth walls. The first sediment to line the flute is mudstone (indicated by the white arrow), which forms a thin layer beneath the turbidites with straight-crested ripples that onlap the edges of the flute. The large red arrow shows palaeoflow direction. Metre scale at top left.

Fig. 10. Amalgamated sandstones at the top of a package at Ross Bay. A sketch of this package with its megaflutes is shown in Fig. 13. The 'classic' megaflute shown in Fig. 9 occurs on the top surface of this package at the eastern (right) end of the outcrop. Note that megaflutes are not restricted to the top surface of the package; three have been outlined within the amalgamated sandstones, with a prominent mudstone lining on the upper one (flute locations in Fig. 13).

spectacular exception occurs at Ross Bay (40 m above base of section in Fig. 4), where megaflutes occur at four stratigraphic levels within a group of amalgamated turbidites ≈ 3 m thick (Fig. 10). The uppermost surface contains the 'classic' megaflute (Fig. 10, number 4), but flutes within the sandstones are also shown in Fig. 10. Elliott (2000b) suggested that the megaflutes are local ornamentations of widespread erosional surfaces that occur on the tops of selected sandstone units, where the vertical spacing of megaflute surfaces varies from 5 m to several tens of metres. However, Fig. 10 (and in other locations such as Kilcloher Head) suggests that megaflutes are commonly more closely spaced than 5 m to several tens of metres, and they are not restricted to single widespread surfaces that occur on the tops of selected sandstone units.

The surfaces that have been scoured by the megaflutes commonly display plan views of well-developed ripples (Fig. 9). The beds that fill the megaflutes onlap the walls of the flutes (Fig. 8), and these may also be rippled. Elliott (2000b, fig. 2) illustrated the 'classic' megaflute at Ross Bay (Fig. 9) and suggested that the linguoid asymmetrical ripples that ornament the remainder of the bedding surface descend into the scour. However, it appears that the sinuous-crested ripples do not descend into the scour (Fig. 9). The first sediment within the flute consists of a mudstone parting about 0·02 m thick (white arrow in Fig. 9), and the bed with straight-crested ripples within the flute overlies this mudstone. A straight groove cast that trends exactly parallel to the axis of the classic flute (040°) cuts through the crests of the sinuous ripples a few metres west of the classic flute. It thus appears that the field of sinuous-crested ripples formed first, and that the flute and groove were subsequently incised into this ripple field.

The 'classic' megaflute (Fig. 9) thus indicates that: (1) a thick amalgamated sandstone with a rippled upper surface was deposited, followed by (2) megaflute erosion and grooving into this bed by a subsequent, different flow; and (3) the megaflute was initially filled with 0·02 m of mudstone (white arrow, Fig. 9). The relatively limited erosion into the linguoid rippled surface suggests that the surface had been coated with a protective layer of mudstone before the arrival of the flow that formed the megaflute and groove.

The megaflute surfaces are widespread erosion surfaces, with a few metres of erosive relief. This can be seen at Kilbaha Bay (Fig. 11), Ross Bay and at Rinevella Point (see below).

Lateral relationships within upper Ross Formation packages

Kilbaha Bay

There are many locations where individual beds, groups of beds and packages can be walked out laterally for hundreds of metres, with the best locations being Kilbaha Bay and Ross Bay. Kilbaha Bay strikes essentially east–west (Figs 1 and 11), and the vector mean flow direction is 010° ($n = 81$ beds). Thus, the lateral view of the beds is almost perpendicular to the mean flow direction. The stratigraphic panel in Fig. 11 is based on the detailed measurement of 10 vertical sections and the walking out of individual beds and packages between sections. The beds are entirely exposed in the cliff and in gently dipping bedding planes that are mostly accessible only at low tide. Four minor faults were recognized, but the beds can be correlated across all faults.

The section can be divided into 20 thickening-upward packages, as described above. The packages are lettered A–R, with D and D1 and O1, O2 and O3 as possible composite packages. The average thickness of the mudstones and thin-bedded turbidites is 0·73 m, and the average thickness of the amalgamated sandstones is 1·14 m. Thus, the packages are a little thinner than those at Ross Bay (Table 1). The average thin-bedded turbidite is 0·053 m thick, and the overlying mudstone is 0·032 m (Table 2, $n = 435$ beds). In the amalgamated sandstones, the average bed thickness is ≈ 0·31 m (Table 2, $n = 287$ beds). The sand percentage in the mudstones and thin-bedded turbidites is 65% and ≈ 99% in the amalgamated sandstones. The average for the entire section is about 84% sandstone. Megaflutes are observed on the tops of 10 packages, and broad scouring without well-defined flutes occurs on top of three more packages. This number of megaflute surfaces is higher than that described by Elliott (2000a, fig. 9b).

The panel diagram in Fig. 11 shows several subtle changes in package thickness, partly controlled by the megaflute erosion surfaces and partly controlled by original changes in bed thickness and facies within packages. Some specific lateral changes are shown in Figs 12 and 13.

Lateral changes in package K (Fig. 12) show thinning in section 3B, where the lower thin-bedded turbidite unit is reduced to 0·1 m of mudstone. Between 3B and 3C, there is a minor increase in thickness from 1·3 to 1·5 m, but major

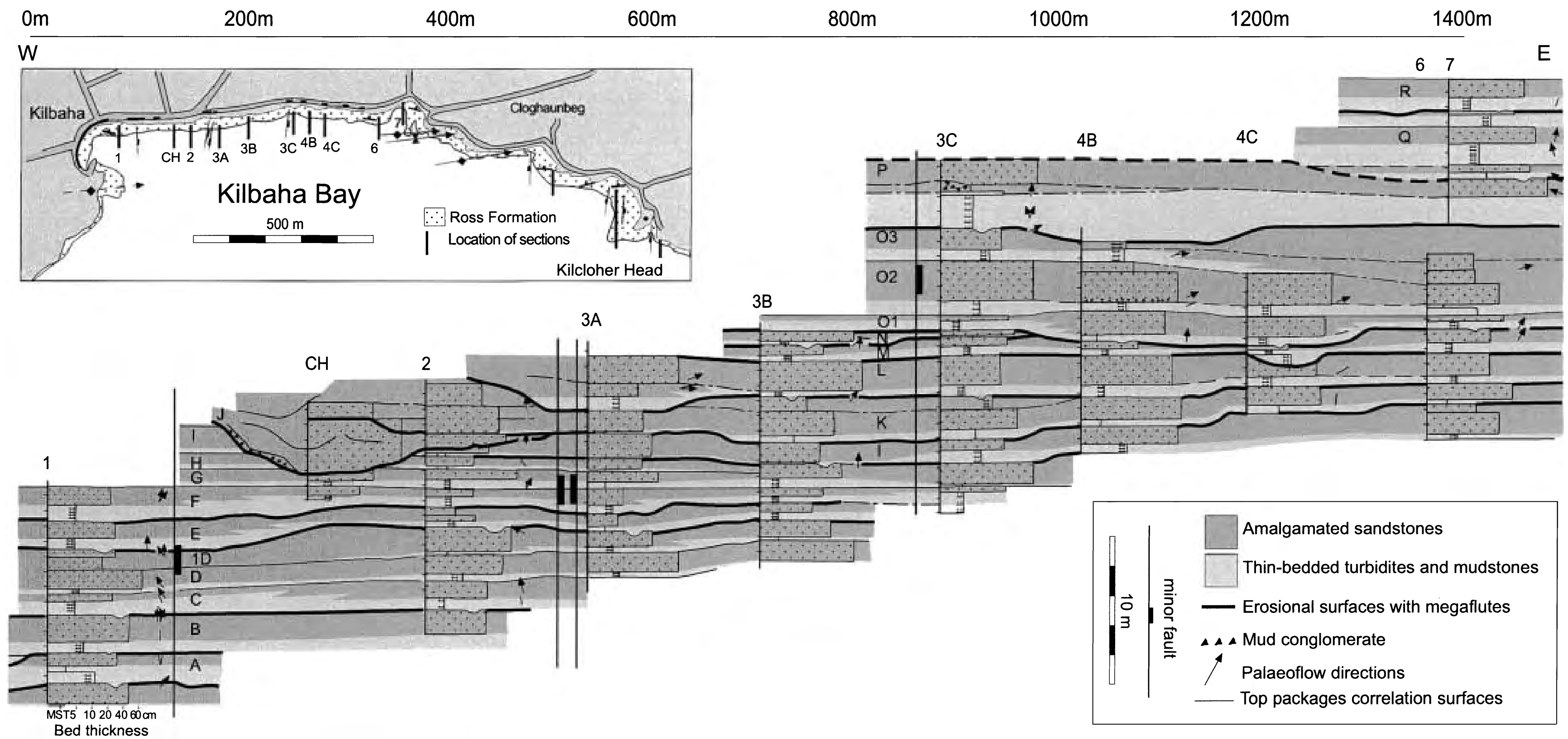


Fig. 11. Lateral variability within packages at Kilbaha Bay. Location of sections shown inset at upper left, and scale of bed thickness shown at lower left. Details of facies relationships, megaflute surfaces and channel (section CH) are discussed in the text.

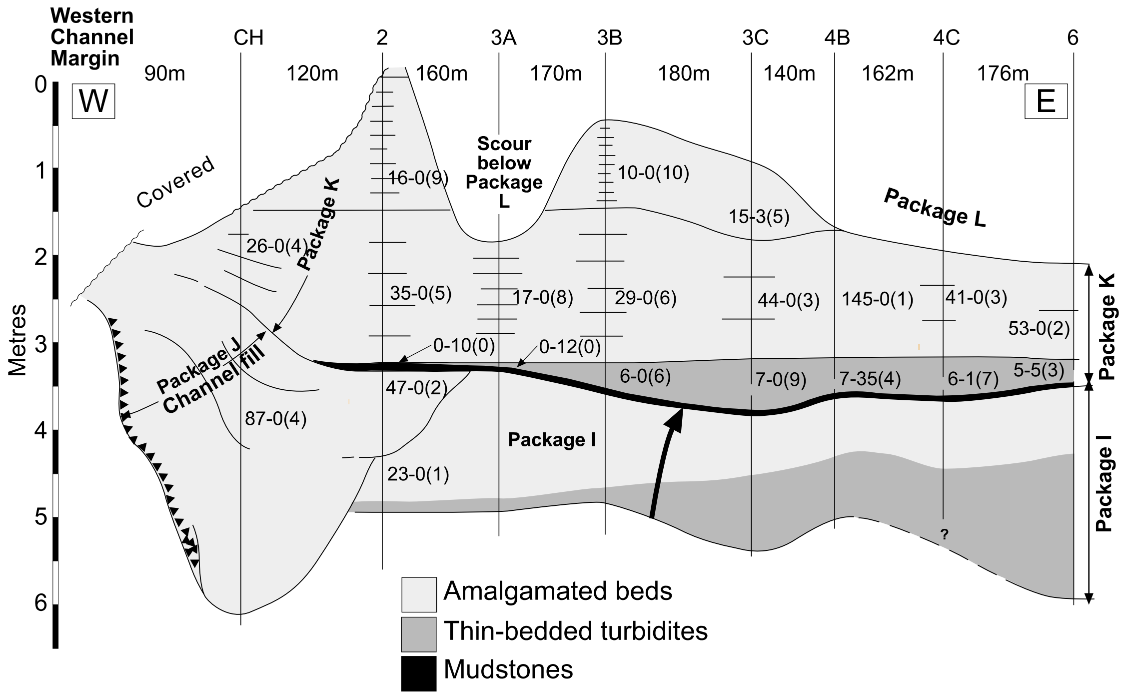


Fig. 12. Lateral changes in packages I, J and K at Kilbaha. Section numbers shown along the top, with spacing between them in metres. Spacing is to scale between sections 2 and 6, but has been increased between the western channel margin and section 2. Within beds, the numbers, e.g. 5–1(7), indicate average sandstone thickness–average mudstone thickness (number of beds). Thus, the 5–1(7) unit is 0·42 m thick. Details of lateral relationships of beds are discussed in the text.

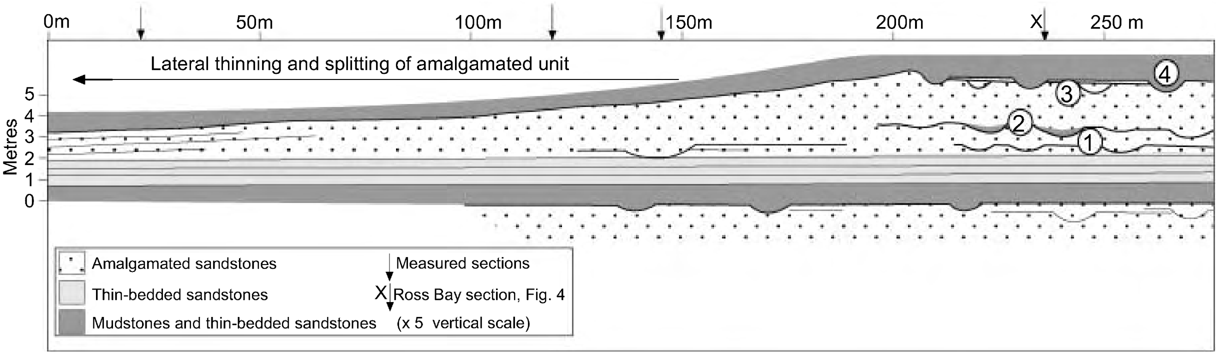


Fig. 13. Lateral facies changes at Ross Bay, in a package about 10 m below the *R. paucicrenulatum/R. dubium* marine bands (Fig. 4). Megaflute 4 is the 'classic' megaflute in Fig. 9, and megaflutes 1 and 2 are shown in Fig. 10. Note the lateral thinning of the amalgamated sandstones, and the splitting into thinner bedded turbidites. Sketch is to scale, with 5× vertical exaggeration.

relative thickness changes involve the thin-bedded and amalgamated turbidites. It is interpreted that the lower amalgamated turbidites in 3B split laterally into thin-bedded turbidites with mudstone interbeds in 3C.

Package K includes the upper part of the largest Kilbaha channel fill (Fig. 11, section CH) and its continuation to the east. A detailed diagram of the beds is given in Fig. 12, where the base of the channel from section CH westward is marked by a mud-clast breccia, with sandstone slabs that may represent collapse of an adjacent channel wall. Figure 12 also shows that, within the channel, the thick amalgamated beds of packages J and K cannot be distinguished. At the eastern channel margin, a thin mudstone parting appears (section 2 in Fig. 12) that can be traced eastward into the unit of mudstones and thin-bedded turbidites that marks the base of package K. Near the channel axis and towards the eastern edge of the channel, the fill consists of thick amalgamated sandstones (four and five beds identified in sections CH and 2 respectively). Eastwards, in sections 3A and 3B, these amalgamated beds have split into eight and six thinner distinct beds respectively. Further to the east, fewer beds can be identified, possibly because of the difficulty of observing amalgamation surfaces. The pattern of bedding in package K therefore appears to represent onlap of mudstones and thin-bedded turbidites towards the east.

Ross Bay

Lateral changes within one package have been studied in detail at Ross Bay (Fig. 13). The package occurs about 10 m below the *R. paucicrenulatum* marine band shown in Fig. 4 and is capped by the 'classic' megaflute shown in Figs 9 and 13 (at the circled number 4). It also contains three other megaflute surfaces (Figs 10 and 13, numbered 1–3) below the 'classic' megaflute surface. General palaeoflow in the package is $\approx 040°$, but the outcrop and the sketch (Fig. 13) trend 090–270°, oblique to flow. Four sections were measured in detail (arrows along the top of Fig. 13), and all the beds were walked out laterally. The lowest part of the package consists mostly of mudstones with a few very thin-bedded turbidites. In places, these mudstones fill megaflutes cut into the top of the previous package. The middle of the package consists of thin-bedded turbidites, which are sharply overlain by thick-bedded amalgamated turbidites about 3·8 m thick in section 1 (Fig. 13). No significant thickness changes in the mudstones and thin-bedded turbidites could be detected, but the thick-bedded amalgamated turbidites become thinner westward from about 3·8 m (section 1) to 1·8 m (at 60 m from the western end of the outcrop). Further west (section 1), the amalgamated beds began to split into thinner bedded turbidites with mudstone partings. The megaflutes are only present where the upper beds are amalgamated, at the eastern end of the outcrop.

Lateral relationships within packages: summary

The studies of lateral relationships and detailed packages at Kilbaha (Fig. 11) and Ross Bay (Figs 12 and 13) suggest seven generalizations.

1 The thin-bedded turbidite facies can thin laterally and pass into mudstones within about 200 m (packages D1 and F).

2 The number of individual beds within a thin-bedded turbidite unit can decrease as the unit thins laterally (package F).

3 Amalgamated thick-bedded turbidites can split laterally and pass into thinner turbidites with interbedded mudstones within about 500 m (packages G and H and, possibly, package I). The same change is seen in an easterly direction from the axis of the Kilbaha channel in package K and in the Ross Bay package (Fig. 13).

4 Thin-bedded turbidites and mudstones tend to drape an underlying scoured topography. The topography is infilled by deposition of amalgamated thick-bedded turbidites (packages F and L).

5 Major thickness changes are associated with the filling of scours, on the scale of megaflutes (up to about 10 m wide) up to broad regional scours over 150 m wide (package L between sections 3A and 3B).

6 The basal sediments in each package consist of mudstones or, more commonly, mudstones with a few centimetre-scale turbiditic sandstones.

7 The thin, lower parts of packages (mudstones and thin-bedded turbidites) can disappear along strike, either by erosion at the base of overlying amalgamated sandstones or by lateral amalgamation and facies change.

Incomplete packages

Many of the packages observed are incomplete and do not have all four elements that make up a complete package (e.g. mudstones, thin-bedded turbidites, amalgamated turbidites and a megaflute surface).

Only about half the packages have undisputed megaflutes on top of the package or within the amalgamated turbidite portion of the package. Only 50% (10 out of 20) of the packages at Kilbaha and 33% (four out of 12) of the packages at Ross Bay have megaflutes. In other locations without extensive bedding planes, megaflutes may be impossible to observe and could therefore be more common than the percentages given above.

The recording of basal mudstones as a separate and distinct part of the package is somewhat dependent on their thickness and on the thickness of sandstones within the mudstones. To be worth measuring as a separate unit, only those mudstones thicker than 0·1 m were recorded, with or without sharp-based sandy or silty laminations $< 0{\cdot}01$ m thick (very thin-bedded turbidites). About 50% of the packages in Kilbaha and about 70% of the packages in Ross Bay have such basal mudstones. As the mudstones become thinner and the interbedded sandstones thicker, they were recorded as thin-bedded turbidites. Many packages begin with thin-bedded turbidites rather than with a distinct mudstone horizon.

In some places, the thick-bedded amalgamated turbidites rest abruptly on mudstones, with poor or no development of thin-bedded turbidites. In these cases, the progressive upward increase in bed thickness cannot be observed. In other places, the thin-bedded turbidite facies may be missing because of erosion at the base of the thick-bedded amalgamated facies, but erosive relationships are rarely observed in outcrop.

Poorly packaged or unpackaged sections

In some parts of the upper Ross Formation (and throughout the lower Ross Formation), there are sections up to about 30 m thick that do not display any form of packaging. Mudstones, thin-bedded turbidites and amalgamated beds appear to be randomly interbedded. The 25 m thick section immediately above the Ballybunion slump/slide at Cloonconeen (Fig. 4) is a good example. Here, the beds consist dominantly of mudstones and thin-bedded turbidites, with only one or two horizons of thick-bedded amalgamated turbidites. There are no apparent thickening-upward trends. It is worthy of note that this section above the Ballybunion slump/slide at Cloonconeen (Fig. 4) is correlative with an extremely well-packaged section at Kilbaha Bay and reasonably well-packaged sections at Kilcloher Head and Kilcredaun Point.

Lower in the Kilcloher Head section (95–130 m above the base, Fig. 4), there is another unpackaged interval. It contains a 5 m thick dark mudstone interval (correlated with a similar interval at Rinevella, Fig. 4), thin-bedded turbidites and several horizons of amalgamated turbidites, but there are no consistent thickening-upward trends. The lower 25 m in the Toorkeal Bay section contains two slumped horizons along with dominantly thin-bedded turbidites, but there are no thickening-upward trends.

Upper Ross Formation channels

Channels up to about 10 m thick and 100 m wide have been observed at several locations in the upper Ross Formation, particularly at the Bridges of Ross (two locations), Kilbaha Bay, Cloonconeen Point, Rinevella Point and in the cliffs below Rehy Hill. Their downchannel lengths are unknown. These channels are described below, emphasizing the nature of the fill, the channel margins and the relationships with adjacent packages.

Cloonconeen Point Channel

Description. The margin of a large channel complex is well exposed at Cloonconeen Point (Fig. 14). The centre of the complex fill is 17 m thick and consists exclusively of amalgamated sandstones, with only a thin mudstone clast conglomerate at the base. The channel margin is mineralized and slightly modified by tectonism, but relationships suggest three phases of channelling and filling. The fill of Phase 1 is overstepped by the base of Phase 2A, and the strike of the channel wall of Phase 2A suggests flow towards 050° (Fig. 14). The basal surface of Phase 2A can be traced laterally from the channel. It truncates thick amalgamated sandstone and continues to rise stratigraphically away from the channel margin, truncating thin sandstone and then a thin mudstone-sandstone package (Fig. 15). The top of the package is defined by the Phase 2A surface, and there is a prominent megaflute (flow direction 054°) on this surface. A thick sandstone (the base is the Phase 2B surface, Fig. 14) onlaps the Phase 2A surface. This sandstone and the Phase 2A surface with megaflutes are draped with dark mudstone. The mudstone can be traced towards the centre of the channel complex, but is cut out by the surface that defines the base of Phase 3.

Channel deposition resumed at the same location with deposition of Phase 3. The lower two beds cut into the underlying mudstones, but higher beds spread from the channel (Fig. 15). About 100 m to the west, the uppermost 3·5 m thick amalgamated channel fill sandstone thins to about 0·7 m, where the bed forms the upper part of a thickening-upward package (Fig. 15).

Interpretation. The Cloonconeen channel illustrates that packages aggrade as a result of spillover from the channel itself (Figs 14 and 15). Phases 1 and 2 may have contributed to the aggradation of packages to the west but, because of erosion at the channel wall, the exact relationships cannot be determined. It is clear that the Phase 2A surface was created as the channel wall stepped westward. Turbidity currents spilled mud onto the megaflute surface, but sand was restricted to the base of the channel. Even the Phase 2B

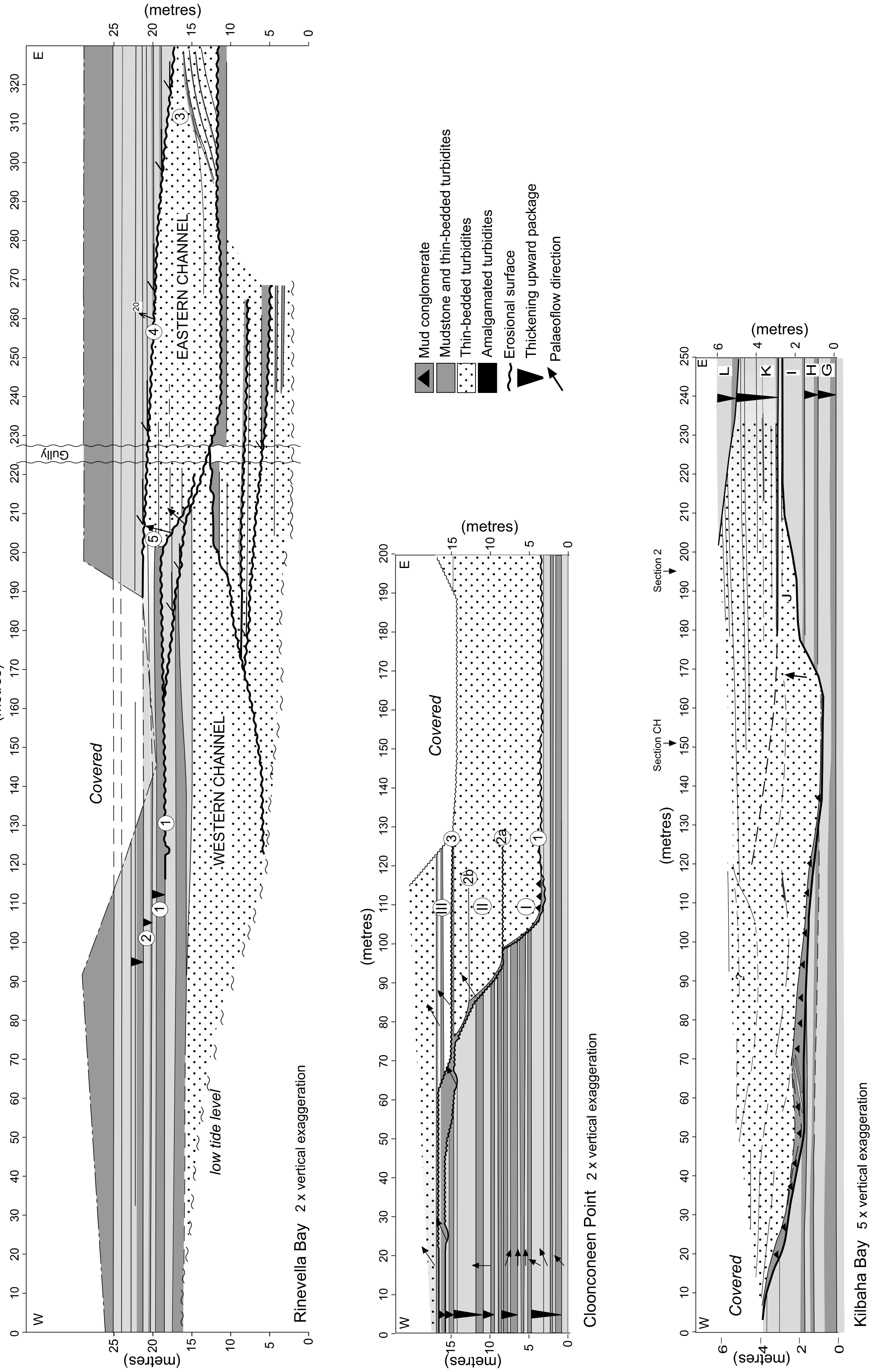


Fig. 14. Sketches of stacked channels at Rinevella Point, Clonconeen Point and Kilbaha Bay. Rinevella and Clonconeen are shown with a 2× vertical exaggeration, and Kilbaha with a 5× exaggeration. See text for details.

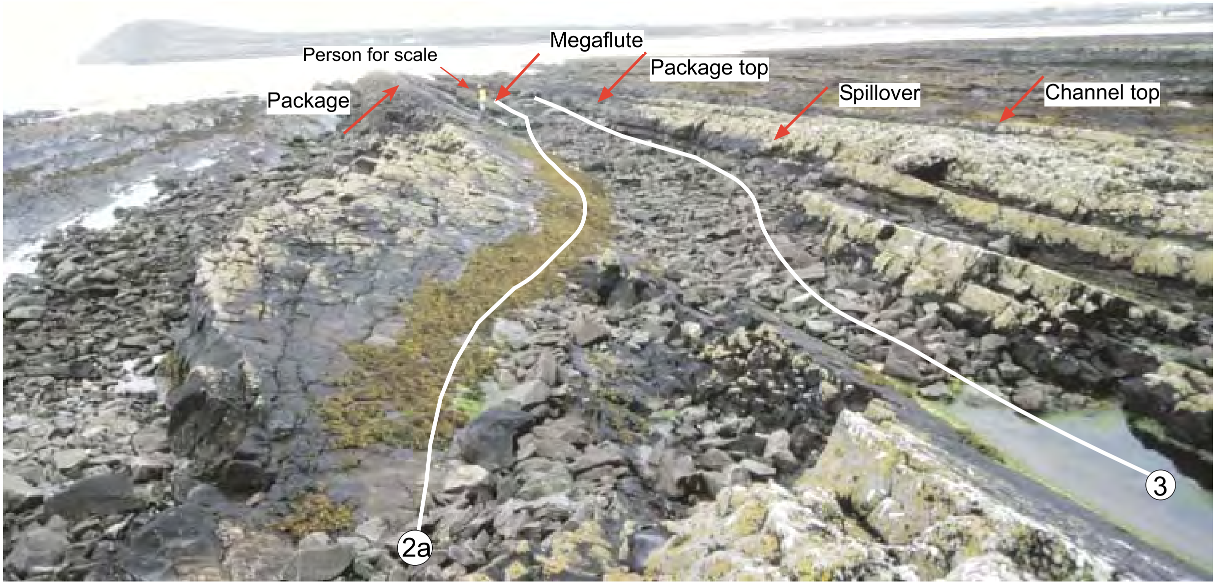


Fig. 15. Channel margin and spillover at Cloonconeen Point, with view approximately to west. White line shows surface 2A, viewed from the channel towards the west. The megaflute arrowed is about 25 m from the western end of the outcrop (Fig. 14). The white line cuts down through the thickest amalgamated sandstone (12·5 m level in Fig. 14) at 80 m from the western end of the outcrop (Fig. 14). Note onlap of channel fill against this erosion surface below surface 3, and spillover and onlap of higher beds (above surface 3) towards the west. The top of the channel fill passes into the top of a package towards the west (Fig. 14).

sandstone onlaps and pinches out against the Phase 2A surface, without major sand overspill (Fig. 14). It appears that, during the principal phase of channel aggradation, mainly mud and thin-bedded turbidites spilled over the margin. Thicker sands spilled overbank more easily after most of the depth of the channel had been filled with sands.

Rinevella Point Channel

Description. The channel complex (Fig. 14) was defined by measuring nine sections and walking out individual beds between the sections. Palaeoflow averages 012°, and the outcrop strikes east–west, roughly perpendicular to flow. The bulk of the outcrop consists of two channel-fill deposits (Fig. 14). The western channel has an erosive, stepped base with an initial relief of at least 5 m (between 180 and 220 m in Fig. 14). The lower 10 m of fill consists of thick amalgamated sandstones, overlain by about 4 m of interbedded turbidites and mudstones (e.g. at 130 m). These turbidites are truncated by a scoured, megaflute surface (circled number 1 in Fig. 14) below package 1 (125 m to the gully). This megaflute surface can be traced eastwards to the base of the eastern channel.

The scouring and megaflutes become unrecognizable west of about 110 m (Fig. 14), and the surface passes conformably into regional bedding. The surface is overlain by thin, tabular thickening-upward packages, of which numbers 1 and 2 (Fig. 14) can be traced eastwards into the fill of the eastern channel (between about 180–210 m).

The eastern channel overlies an extensive mudstone layer about 1 m thick. The channel base is planar (at about the 12 m stratigraphic level, Fig. 14), and its eastern end is overlain and downlapped by a wedge of sandstone beds (290–320 m in Figs 14 and 16). These surfaces downlap perpendicular (westward) to the channel flow direction (northward; Fig. 14) and are interpreted as laterally accreting sandstones. After a phase of lateral accretion, the fill became aggradational. The first aggrading sandstone is restricted to the base of the channel, but passes laterally eastwards into a thin mudstone that drapes the lateral accretion surface (circled number 3, Fig. 14, 300–320 m). The bulk of the fill consists of 10–11 m of amalgamated sandstones (e.g. at 240 m), but these thin eastwards to about 2 m at the easternmost end where the outcrop is lost beneath the sea. The uppermost surface (circled number 4) between 205 and 325 m is an erosional megaflute surface. The overlying beds onlap progressively to the west. Thick tabular sandstones continue to

Fig. 16. Base of channel at Rinevella Point resting on thick mudstone, with the first deposits above the channel base consisting of laterally accreted (L.A.) sandstone. The uppermost L.A. surface (surface 3 in Fig. 14) is onlapped by the first vertical accretion sandstone (V.A., with onlap to the right), which passes into mudstone up the channel wall (i.e. the lateral accretion surface). The majority of the channel fill consists of amalgamated sandstones (left side of photo, 10 m thick).

the 25 m level, where the entire channel complex is overlain by at least 4 m of mudstones. At the western end of the eastern channel (180–210 m), the amalgamated sandstones split into thickening-upward packages 1 and 2 (Fig. 14). The scoured megaflute surface is overlain by mudstone, and amalgamated channel sandstones cut into this mudstone at about 200 m (circled number 5). Above the mudstone, the amalgamated channel sandstones spill overbank and split into the thinner bedded turbidites and mudstones in packages 1 and 2.

Interpretation. The most important relationships are shown by the eastern channel, which is interpreted to have first accreted laterally towards the west. The initial phase of lateral accretion was followed by a phase of vertical accretion. The first turbidity currents transported sand close to the channel floor, with some mud spilling up onto the eastern channel margin (the former lateral accretion surface, circled number 3 in Figs 14 and 16). This supports the interpretation that mud can spill out of the channel during aggradation, as is seen on the megaflute surface west of about 200 m. The channel fill aggraded, without any suggestion of sand spilling overbank, to the point where the channel fill cut into overbank mud (circled number 5 in Fig. 14). With the channel mostly filled, flows were able to spill extensively over the banks to form packages 1 and 2 that continue to the western end of the outcrop. The top of the second package is the erosion surface that dips eastwards across the top of the eastern channel (circled number 4, Fig. 14). The Rinevella channel shows some of the same features as the Cloonconeen channel, namely that turbidity current sand is at first restricted to the base of the channel and only mud can be spilled overbank. Sand can only spill overbank after considerable channel aggradation. When it does so, the sand commonly overlies mudstone and contributes to the building of thickening-upward packages.

Kilbaha Bay Channel

Description. The channel at Kilbaha Bay (Fig. 11, section CH) was reconstructed from measured sections and a photomosaic (Fig. 14). The observed depth of incision is about 3 m, and the channel fill facies totals about 6 m. Small scours and flutes at the base of the channel give an average palaeoflow direction of 003°. The base of the channel is relatively flat and follows the mudstones at the bases of packages H and I. A mudstone clast conglomerate up to 1 m thick and 150 m wide marks the western side of the channel base. The conglomerate also contains two elongated sandstone blocks up to 3·5 m long and 0·35 m thick. Within the channel, there are several broad scoured surfaces marked in places by mudstone clasts. The channel fill consists of amalgamated thick-bedded sandstones.

The relationship of the channel fill to beds outside the channel is not exposed on the western side. However, on the eastern side, the thick amalgamated channel-fill sandstones split laterally into thinner bedded sandstones separated by thin mudstone partings. The most prominent parting has been used to separate the main amalgamated channel fill (assigned to package J) from the fill defined as package K (Fig. 12). Note that package K can be traced laterally from the channel continuously for about 990 m to section 6, as discussed above.

Interpretation. Lateral facies changes (Fig. 12) suggest that mudstone and thin-bedded turbidites spilled over the eastern channel wall, initiating deposition of package K. Powerful flows continued in the channel axis, with aggradation of amalgamated structureless sandstones, but these beds split eastward into interbedded sandstones and mudstones. This relationship suggests overbank spillage of sand and mud to the east, forming the upper part of package K at the same time as the channel deposits were aggrading into a succession of uninterrupted amalgamated sandstones (section CH in Fig. 11).

Bridges of Ross channels

At least three distinct channels have been recognized at the Bridges of Ross (Figs 17 and 18). The channels lie about 500 m WNW of the car park at the Bridges of Ross (Fig. 1) and are exposed in a long cliff face striking north–south above a very continuous bedding plane that forms a dip surface into the sea (Fig. 17). This bedding plane can be traced south (left) and west of the cliff shown in Fig. 17, and the channel can be examined in detail on all three faces of the cliff. These channels have also been described by Elliott (2000a), Martinsen *et al.* (2000) and Wignall & Best (2000).

A prominent mudstone clast conglomerate marks the base of the lowermost channel. The fill of the channels consists of amalgamated sandstones totalling about 6 m in thickness, with several mudstone clast horizons (Fig. 18), which mark the channel walls (Fig. 17). The middle channel partially cuts into the first and truncates the basal mudstone clast conglomerate. The wall of the truncation trends 330–150°. On the south side of the outcrop, the south wall of the channel is well exposed with erosional relief of at least 2 m. Directions obtained from the strike of the channel wall are 310–130° and 320–140°.

The third channel cuts into the fill of the second channel, and has a measured thickness of 5·4 m (Fig. 18). The fill consists entirely of amalgamated sandstones, and three small steps (ST in Figs 17 and 18) can be seen at the base of the channel, trending east–west. On the western side of the outcrop, small flutes occur on the base of the channel fill, with north-westward flow directions (Fig. 18). Because the flutes indicate a north-westerly flow direction, the strike of the wall of the second channel (330–150°, 310–130° and 320–140°) is interpreted to imply north-westward rather than south-eastward flow.

Because the channels are preserved in an isolated blocky cliff (Fig. 18), contacts between the channel fill and surrounding facies are generally not exposed. The wall of channel 2, as seen on the west face of the cliff, is a spectacular exception. Here, the channel wall strikes north-westward and dips as steeply as 54° to the north-east. The depth of incision is at least 5 m, with the channel cutting into thick-bedded turbidites with thin mudstone partings. There are mudstone clast conglomerates at the margin, as well as some steeply dipping but otherwise undeformed sandstones that drape the channel wall. The channel is filled with thick amalgamated sandstones, and beds in the upper part of the fill spill over the margin (Fig. 19) and become conformable with the beds outside the channel.

Fisherman's Point channels

Fisherman's Point lies about 1·2 km ENE of the Bridges of Ross (Fig. 1) and presents an impressive view of bedding discordances in the cliff. The wide bedding plane in the foreground (Fig. 20) is the top of the Ross Slide, where several superbly developed sand volcanoes can be examined. Three discordances are identified in Fig. 20. Discordance 1 is almost planar over the north-western half of the outcrop and truncates a broad syncline and minor anticline–syncline pair in the centre of the outcrop. The beds must have been folded before discordance 1 developed and can be interpreted as a thrust fault. This interpretation is supported by the presence of mineralization and slickensides along the discordance plane. Discordance 2 is mostly inaccessible, but interpreted as a thrust fault suggested by the bedding geometries. Discordance 3 is also characterized by extensive mineralization and slickensides, and there are minor drag folds that suggest some thrust movement towards 350°. However, on the south-eastern side of the fault, several beds clearly onlap the plane of discordance, and the thin-bedded turbidites north-west of the discordance cannot be

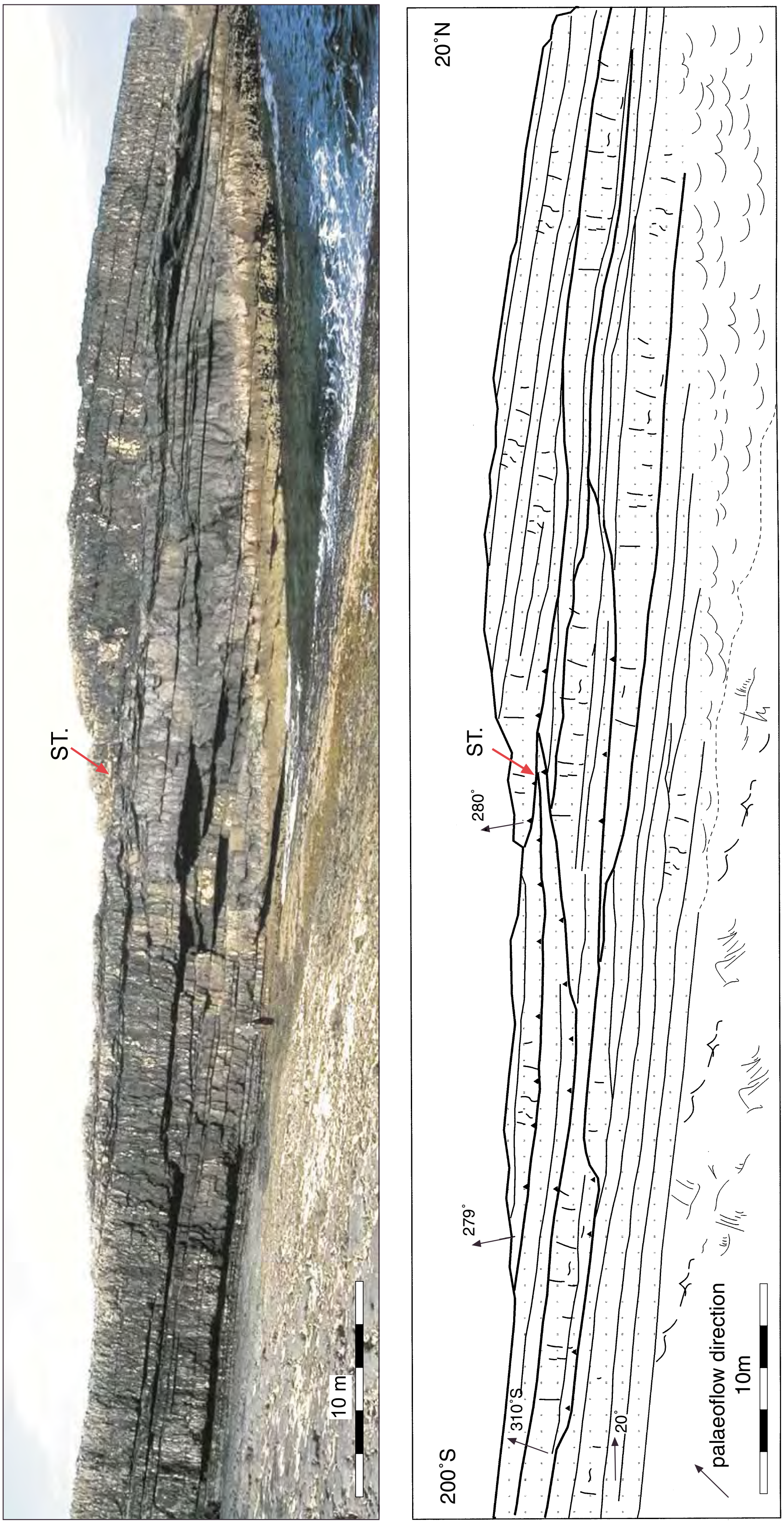


Fig. 17. Eastern cliff face at the Bridges of Ross, oriented 200–020°. Photo and sketch show multiple small channel incisions marked by mudstone clast conglomerates. Palaeoflow arrows are oriented with respect to the orientation of the face. ST indicates small steps at the base of channel 3. See text and Fig. 18.

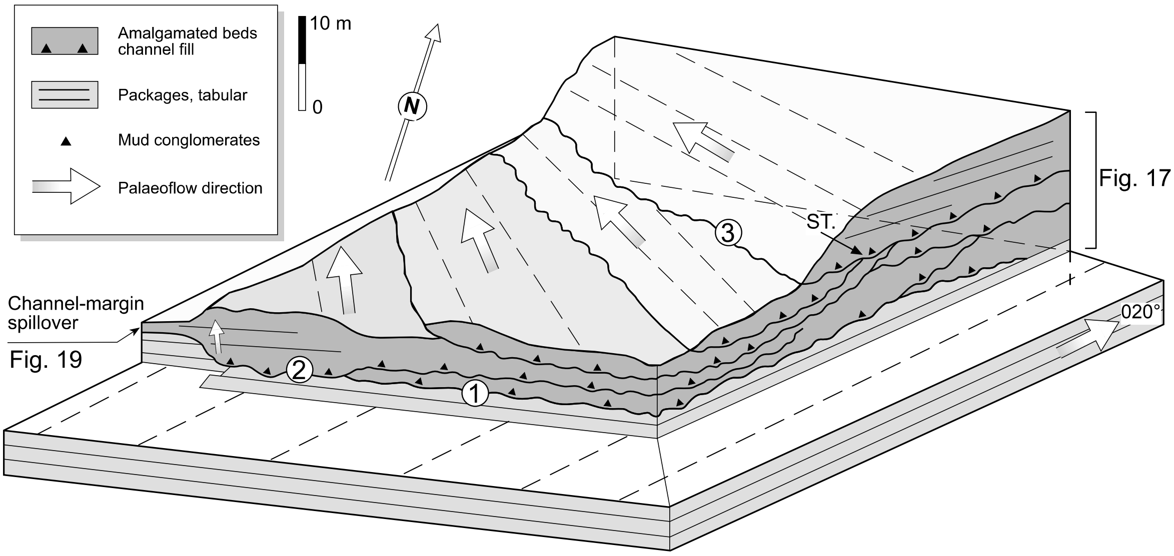


Fig. 18. Sketch of blocky cliff at the Bridges of Ross. Face on the right is shown in Fig. 17, with ST indicating the steps at the base of channel 3 (palaeoflow 270–090°, 270–090° and 275–095°). Channel 1 (circled) is cut by channel 2 (wall trends 330–150°, 310–130° and 320–140°), and the margin of channel 2 is well exposed on the west face of the cliff. Both channels 1 and 2 have multiple internal surfaces marked by mudstone clast conglomerates. The rollout and spillover of the channel 2 fill (Fig. 19) is indicated at the 'channel-margin spillover'. On the western side of the outcrop, small flutes occur at the base of the channel fill, with flow directions of 272°, 275°, 277°, 280°, 285° and 290°.

Fig. 19. West-facing cliff at the Bridges of Ross (Fig. 18), showing the wall of channel 2. Beds dip steeply against the wall (defined by the truncation of sandstone on which the field assistant sits), and white arrows show beds spilling out of the channel and flattening into the regional bedding outside the channel.

matched across the discordance. Discordance 3 is interpreted as a channel margin, with later minor thrusting. The channel fill above discordance 3 is about 13·5 m thick and consists dominantly of amalgamated sandstones, with a prominent mudstone clast conglomerate up to 1 m thick marking the basal channel fill.

There are few palaeoflow indicators, but two sole marks (including small flutes in rows, resembling rill marks) just above the base suggest flow towards 290°. Ripple crests in the thinner bedded unit about 3 m above the base indicate flows towards 055°, and a broad, rippled surface 2 m below the top indicates flow towards 090°. The variety of directions suggests that the lower 3·25 m of fill, immediately above the mudstone clast conglomerate, were deposited in a channel heading almost westwards. The main part of the fill may represent a different channel, stacked on top of the lower one, heading north-east to east. The relationships of channel fill to beds outside the channel cannot be seen.

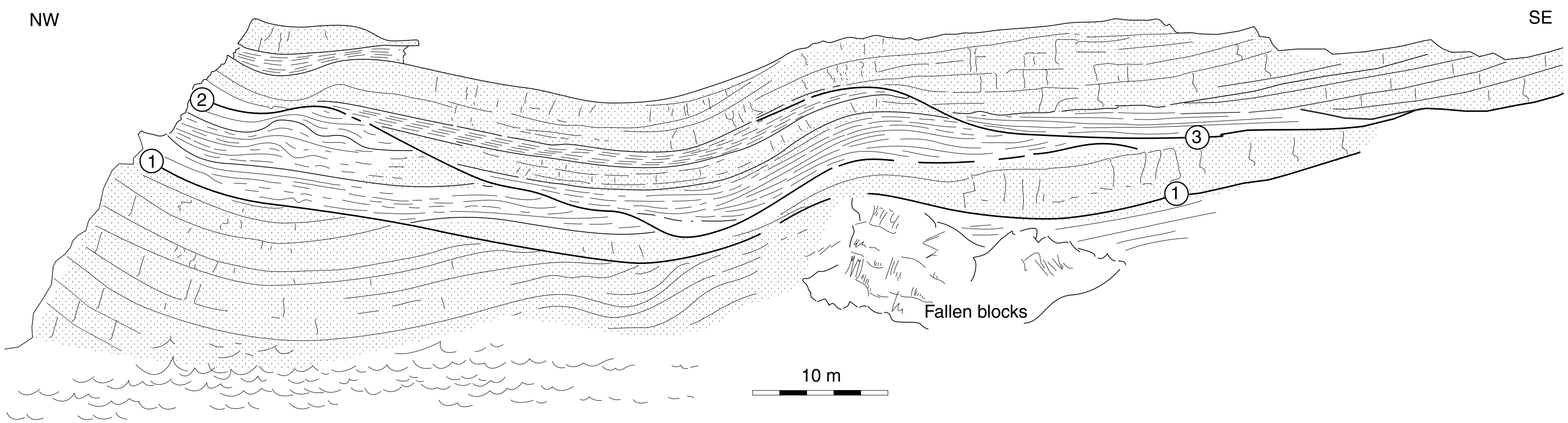


Fig. 20. Photo and sketch of cliff at 'Fisherman's Point' – note fisherman halfway up cliff on left (and 10 m bar) for scale. Surface 1 is almost planar and truncates folded rocks, and is best interpreted as a thrust rather than a channel wall. Note onlap of thick amalgamated beds against surface 3, suggesting channel incision. However, surface 3 is also mineralized and possesses slickensides. The original channel wall has formed a surface used as a slip surface in subsequent minor thrusting.

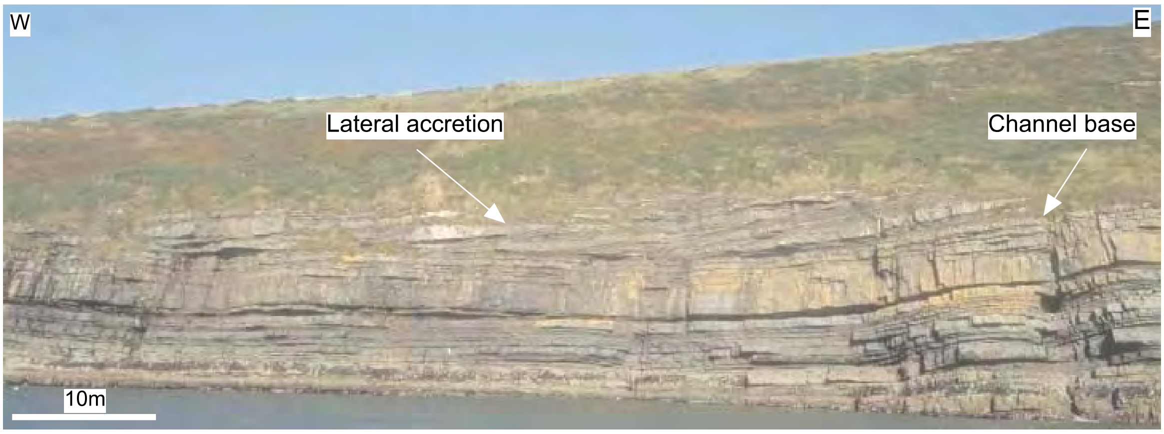


Fig. 21. Cliff below Rehy Hill where the regional bedding is horizontal. The dark recessive intervals are mud-clast conglomerates, and the sandstones dip gently to the left at the cliff top. The sandstones pinch out towards the top and towards the lower downlap surface, giving sigmoidal bed shapes. The thickness of the set of dipping beds is about 6–8 m, and the length of the set is about 200 m. The dipping beds are interpreted as lateral accretion deposits; see text for details.

Channels in the cliffs below Rehy Hill

The cliffs below Rehy Hill are mostly inaccessible, but can be observed from a boat. The beds are generally flat-lying but, in one location, interbedded sandstones and mudstones dip at about 5° with respect to the horizontal (Fig. 21). The thickness of the dipping interval is estimated at 6–8 m, and the lateral extent is > 200 m. The dipping beds are sigmoidal and lenticular, with each bed pinching out at the lower downlap surface, and apparently also at the upper surface (which is partly covered). At the eastern end, the dipping beds consist of interbedded sandstones and mud-clast conglomerates but, towards the west, the section contains more amalgamated sandstones. The set of dipping beds with associated mud-clast conglomerates represents deposits of high-energy flows and is interpreted as a lateral accretion deposit, as in the past interpretations of Chapin *et al*. (1994) and Elliott (2000a). Inclined mud-clast conglomerate layers are also described in this paper at the base of channels at Bridges of Ross, and are a very useful indicator of channel-fill deposits. There are also some other candidates for channels in these cliffs, presented by Chapin *et al*. (1994) and Elliott (2000a, fig. 11) where, in the latter, channel complex 2 is shown with one wall of 2–3 m of relief. Channels 1 and 3 do not have erosional walls. Channel 1 consists of thick amalgamated sandstones that split laterally westwards to form the 'wing' of channel 1, and channel 3 also appears to consist only of thick amalgamated sandstones without channel walls and without wings. Observations of these cliffs suggest that erosional channel walls and bases are generally absent, as are basal layers of intraformational mud clasts. If channels 1, 2 and 3 are channels, they are clearly of a different type from those described above from the Bridges of Ross, Kilbaha Bay, Cloonconeen and Rinevella. The thick amalgamated sandstones, splitting into thinner beds, could equally well represent overbank deposition of the type documented above.

Channellization: summary

Channel fills, channel margin relationships and lateral accretion deposits can best be observed at the locations described above. Channel margins are commonly steep and stepped, with a visible relief of up to 5 m. Each channel fill is underlain by a mudstone clast conglomerate, and the bulk of the fill is characterized by a thick succession of vertically aggraded amalgamated sandstones that onlap or scour into the channel margin. On the 'point bar' side of the channel, lateral accretion deposits may be present. The upper part of the 'cut bank' channel wall commonly flattens out and passes laterally into a bedding surface with megaflutes – a good example is the western side of the eastern channel at Rinevella Point (Fig. 14), where the gently rising margin with megaflutes extends more than 100 m from the channel before passing into a bedding plane.

A tentative generalization from these observations is that, in other outcrops of the upper Ross Formation, where clear evidence of channel margins and channellization is not present, a succession of thick amalgamated sandstones underlain by a mudstone clast conglomerate nevertheless indicates a channel-fill environment. This can be seen at Fisherman's Point on the east–west striking cliff face of Fig. 20.

SLUMPS AND SLIDES

The upper Ross Formation (unlike the lower Ross Formation) contains several spectacular deformed horizons up to 30 m thick. These have been interpreted as slumps and slides, and one has been informally named the Ross Slide (Gill, 1979). Two more slides are informally named in Fig. 4. Descriptions have been given by Martinsen (1989), Martinsen & Bakken (1990) and Strachan (2002), mainly of the Ross Slide and examples from the Gull Island Formation, where the slumps and slides are much more abundant than in the upper Ross Formation. The correlation in Fig. 4 suggests that there are three main slump/slide horizons in the upper Ross Formation, with two thinner slump/slide horizons at Toorkeal Bay. The slump/slide horizons are tentatively correlated based on their occurrence in relation to the marine bands (Fig. 4).

The 'paucicrenulatum' slump/slide

This occurs immediately below the *R. paucicrenulatum* marine band at Ballybunion, Kilcredaun Point, Clooncooneen Point and Kilcloher Head. It is 8–10 m thick and has varying proportions of sandstone and mudstone. At Clooncooneen Point and Kilcredaun Point, the slump contains several folded sandstones, whereas the slump consists mostly of mudstones at Ballybunion and Kilcloher Head. This implies major lateral facies variations within the slump or suggests that different slumps and slides may occur at one stratigraphic level. Indicators (such as slump folds) of slump/slide movement direction can only be observed at Ballybunion, where the movement was southward (Fig. 4).

The Ross Slump

This slump was informally named the Ross Slide by Gill (1979) but, based on the internal deformation, the Ross Slide should be described as a slump (*sensu* Stow *et al.*, 1996; Strachan, 2002). It occurs about 20 m below the *R. paucicrenulatum* marine band at Bridges of Ross, Ross Bay and near Gull Island. It is 6–7 m thick and is the best known and most commonly visited slump in the Ross Formation (for details, see Strachan, 2002). In places, the slump consists dominantly of mudstone but, elsewhere, it can be sand rich. Deformation includes soft-sediment folding and thrusting, with some evidence that sandstones have sunk (loaded) down into mudstones during sliding. At the Bridges of Ross, bedding dips gently, and the slump can be traced laterally for almost 1 km. At the base of the slump, there is an asymmetrical anticline with a thrusted core, with fold and thrust strikes of about 120° and implied movement towards 030°. The surface over which the slide moved is marked by small grooves, visible only close to the preserved edge of the slide. Directions are 022°, 040°, 048° and 065°, which, along with the thrusted fold, suggest north-eastward movement at the Bridges of Ross. The top of the slide is marked by a thin, flat-based turbidite, and the contact can be interpreted in at least two ways. The simplest interpretation is that any topography that developed on top of the slide during movement was planed off by erosion immediately before deposition of the flat-based turbidite. It could alternatively be argued that, during final dewatering of the slide, the top layers of sediment were sufficiently fluid that they flowed to produce a flat top to the slide (Strachan, 2002).

Sand volcanoes are prominent on top of the slide, reaching diameters of over 1 m and heights above the slide surface of at least 0·5 m (Gill & Kuenen, 1958; Gill, 1979; Strachan, 2002). The circular shapes of the volcanoes, their radial symmetry and their well-preserved central craters suggest eruption of sand at the sediment–water interface, rather than after deposition of overlying mudstones. None of the volcanoes shows any sign of erosion, suggesting that the next turbidity current failed to erode the top of the slide or the volcanoes themselves (see Strachan, 2002).

The Ballybunion slump/slide

This occurs about 40–50 m below the *R. paucicrenulatum* marine band at Ballybunion, Kilcredaun Point and Clooncooneen Point (Fig. 4). The correlation of the slump/slide is based on the occurrence of the *R. paucicrenulatum* marine band. At Ballybunion, the 30 m thick unit is well exposed in three dimensions and shows several distinct styles of deformation. Towards the base, a thick sandstone horizon has been folded and thrusted within the slide. Fold axes strike 155°, 110°, 110° and 150° (mean 138°), with vergence and implied movement towards the north-east.

This horizon is overlain by deformed mudstones and a second sandstone horizon that appears to be deformed mainly by large-scale lateral breaking-up of the bed by loading. Above the sandstone, there is a capping layer of mudstones. These contain ≈0·5 m long narrow sandstone dikes that have injected upwards from a sandstone layer that has essentially disappeared. After dike injection, several synsedimentary thrusts were formed, with thrust planes striking 060°, 064°, 065°, 070° and 075° (mean 067°) and dipping north-westward. The implied direction of thrusting and compression is therefore towards the SE. Small folds (axes trend 055°, 060° and 060°) suggest movement towards the SE. The different directions in the lower and upper parts of the slump suggest that there may be two different slumps superimposed. Alternatively, different parts of the slump may have moved in different directions, perhaps as the centre moved forward and the margins spread laterally.

PALAEOFLOW

Palaeoflow measurements have been obtained from 603 beds, with a vector mean of 048° (Fig. 3). However, it is necessary to break down the palaeoflow data in different ways to extract much more information than the vector mean for all of the Ross Formation.

Flow directions related to facies

At Ross Bay and Kilbaha Bay, there are sufficient data to plot separately the palaeoflows for the thin-bedded turbidite facies and the amalgamated thick-bedded facies. At Ross Bay, 74 beds were measured, with an overall vector mean of 048°. When the data are separated (Fig. 22), it can be seen that the spread of readings is much greater for the thin-bedded facies (285° to 135°) than for the thick-bedded amalgamated facies (345° to 115°). In the thick-bedded amalgamated facies,

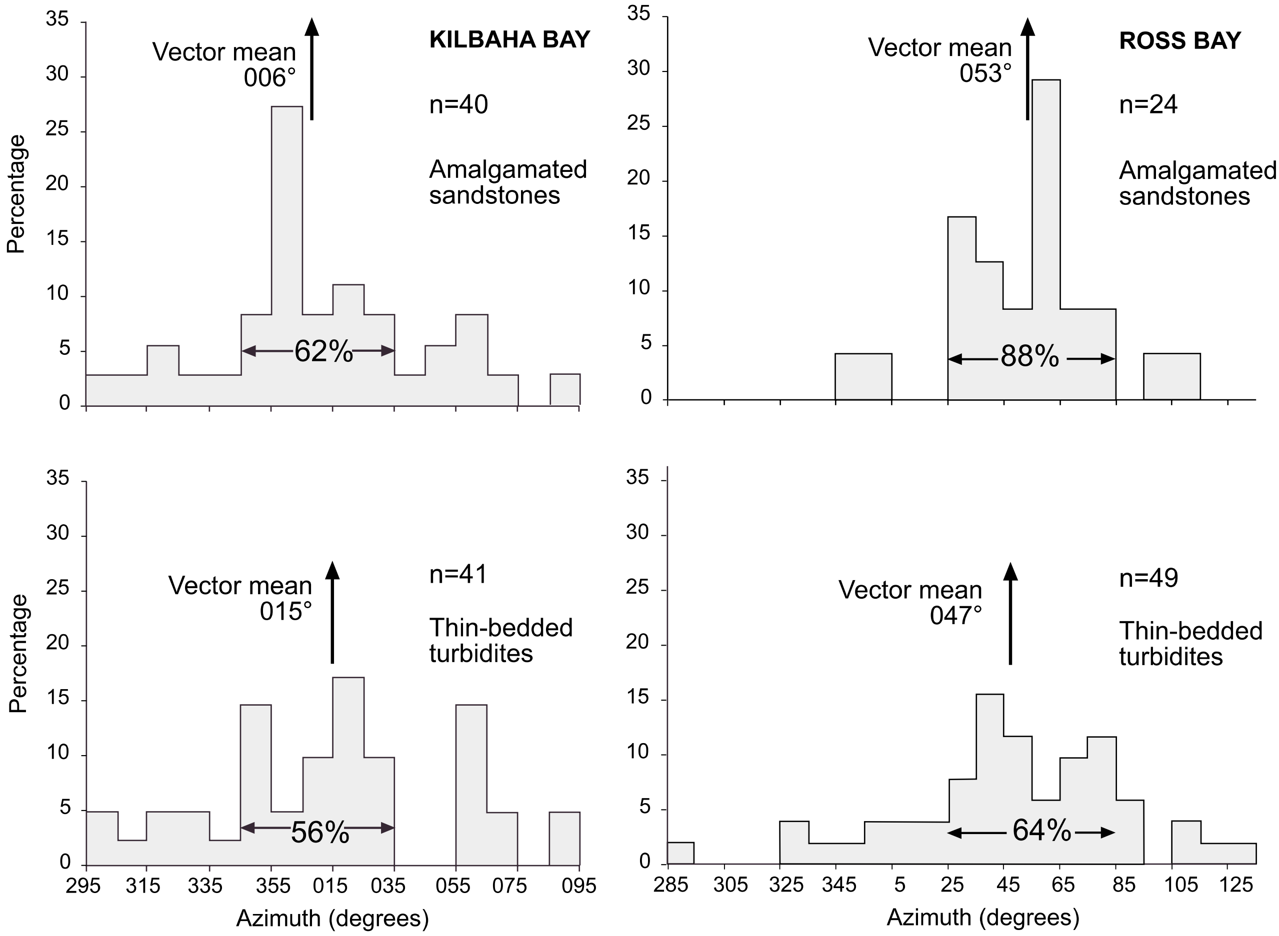


Fig. 22. Histograms of flow directions from Ross Bay (right) and Kilbaha Bay (left). Upper histograms show data for the amalgamated thick-bedded facies, and lower histograms show data for the thin-bedded facies. Note the concentration of most of the data into a much narrower palaeocurrent range for the amalgamated thick-bedded facies.

88% of the readings fall in the central part of the distribution (025° to 085°), compared with only 64% for the thin-bedded facies. The vector means for the two facies are similar (053° for amalgamated and 047° for thin bedded). A similar distribution (Fig. 22) is seen at Kilbaha Bay, where the vector mean for all 81 readings is 010°. Although the overall spread for each facies is similar, the distribution is much more peaked for the amalgamated facies, with almost 33% of the readings falling in the 355° to 005° range. The vector means for the two facies are similar (006° for amalgamated and 015° for thin bedded). It therefore appears that most of the flow directions for the amalgamated facies are concentrated in a much narrower spread than those of the thin-bedded turbidite facies, regardless of the overall vector mean (048° at Ross Bay, 010° at Kilbaha Bay) of the data.

INTERPRETATION – FACTS TO BE CONSIDERED

All the features described above will be built into an overall interpretation that will include: (1) the absence of packaging in the lower Ross Formation and parts of the upper Ross Formation; (2) the abundance of packaging and megaflute surfaces in the upper Ross Formation; (3) the lateral facies changes detailed at Kilbaha and Ross Bay, particularly the splitting of amalgamated sandstones into turbidites interbedded with mudstones, and the thinning and loss of turbidites laterally into mudstones; (4) the facies relationships within channels and at channel margins; (5) the detailed relationships between channel fills and adjacent packages; (6) flow directions in the thin-bedded turbidite and thick-bedded amalgamated sandstone facies; and (7) the nature of the interbedded slump/slide horizons.

Interpretation of packaging: lobes or channel spillovers?

Many parts of the upper Ross Formation are characterized by thickening-upward packages (Fig. 7), similar to those traditionally interpreted as prograding lobe deposits (Mutti & Ghibaudo, 1972; Mutti & Ricci Lucchi, 1972; Mutti & Normark, 1987). The successions in the Ross Formation, averaging a little over 2 m thick, could be considered typical of a lobe fringe (Mutti & Normark, 1987). However, an alternative interpretation is possible. Traditional lobe interpretations are unlikely in the Ross Formation because: (1) thick amalgamated sandstones would not be expected at the lobe fringe; (2) thin lobe fringe deposits would not commonly be closely associated with channel-fill deposits, as they are at Cloonconeen, Rinevella and Kilbaha; and (3) megaflute erosion surfaces would not normally be associated with abandonment of the lobe fringe.

The intimate relationship between packages and channels suggests that the thickening-upward successions seen in packages are the result of lateral channel migration and aggradation. Overbank spill deposits thin and split laterally away from the channel (Figs 11–13), and the most distal spillover deposits at hypothetical location X would consist of mudstones at the base of a package. As the channel migrates laterally towards location X, spillover deposits at location X would consist of thin-bedded turbidites. During further channel migration and filling, spillover at location X, closest to the channel itself, would consist of thick-bedded and amalgamated turbidites. Turbulence associated with spillover may have formed the megaflutes that occur within the amalgamated facies and on top of many of the packages. This hypothesis is supported by the observation that thick-bedded amalgamated turbidites commonly split laterally into thinner bedded turbidites separated by mudstone partings (e.g. Figs 11 and 13). The lateral splitting would represent deposition further away from the channel, with less erosion between beds and hence more preservation of interbedded mudstones. These lateral spillover relationships have been sketched in Fig. 23. The thickening-upward package at location X would be abandoned by a shift or avulsion in the channel position. The mudstones at the base of the next package in location X would then represent deposition furthest from the new channel. The scenario of progressive lateral channel migration is also supported by the presence of surfaces that can be interpreted as having formed by lateral accretion (Rinevella, Figs 14 and 16; Rehy Cliff, Fig. 21).

A similar interpretation of sheet-like turbidites as channel wings was suggested by Elliott (2000a), where the megaflute surfaces were interpreted to define the base of channel wings. However, contrary to Elliott (2000a), the present paper suggests that the packages form during channel migration, and that the megaflute surfaces indicate the top, not the base, of the channel wings.

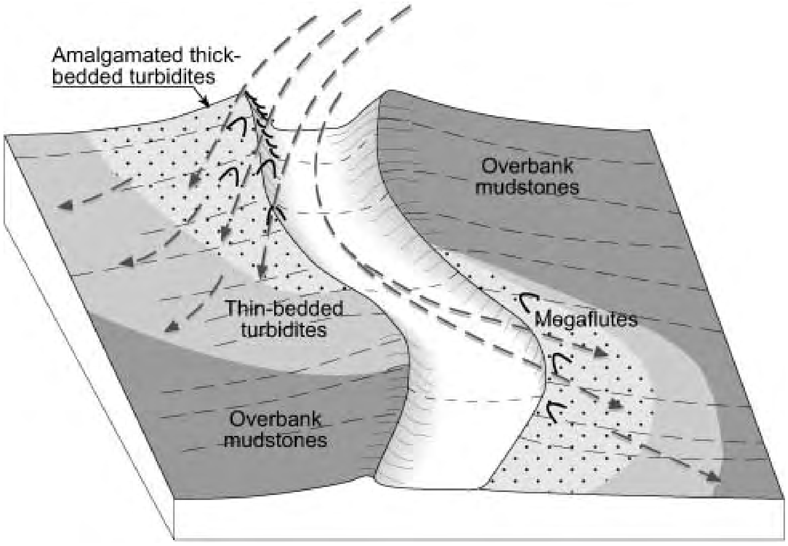


Fig. 23. Block diagram showing development of spillover lobes. At cut-bank channel corners, spillover forms amalgamated thick-bedded turbidites closest to the channel. These beds pass laterally away from the channel into thin-bedded turbidites and mudstones. On point-bar corners, the spillover is probably muddier. Note the proposed association of megaflutes with channel-wall scouring and amalgamated sandstone deposition. Such erosional megaflutes at channel margins are also described from the Navy Fan by Normark & Piper (1991). Note also the small curves indicating a stepped channel wall on the cut-bank side (top of diagram). Diagram is not to scale; channel width before lateral shifting is about 100 m, and sandy spillover deposits (light grey and grey) may reach up to 2–3 km long.

In conclusion, based on the text above, the thickening-upward packages are not interpreted as prograding lobes, but are intimately related to channels and may have formed during lateral channel migration and aggradation.

A two-stage model of channel filling and channel migration

The lateral extent of some of the amalgamated sandstones and thin-bedded turbidites (at least 1 km at Kilbaha, Fig. 11) could be taken to indicate that similar distances of channel migration might be necessary in order to build the vertical facies successions in the packages (i.e. distal mudstones overlain by thin-bedded turbidites and finally by amalgamated sandstones at the channel margin). However, there are no outcrop indications of long-distance channel migration, and the width of the dipping surfaces at Rehy Hill is only a few hundred metres. A two-stage model of channel migration and aggradation is therefore proposed (Fig. 24).

The first phase involves avulsion of a channel into a new area, the development of sinuosity and the beginning of lateral accretion at channel bends. Turbidity currents erode the cut-bank side of the channel, and sand, mud and mud clasts can spill onto the point-bar side and be deposited (Fig. 24). The upper parts of some of the flows can also spill over the cut bank and deposit mudstones and thin-bedded turbidites close to the channel, as at Cloonconeen and Rinevella (Fig. 14). There is no evidence in the field for the development of topographic relief (levees) at the channel margins, hence the terminology of spillover rather than levee. Lateral accretion deposits appear to be rare in the upper Ross Formation and, hence, the first stage of package development may be relatively brief. A relatively short lateral accretion distance is suggested in Fig. 24.

The second phase involves vertical aggradation and channel filling (Fig. 24). The first in-channel deposits may be restricted to the channel floor but, as the channel fills, more and more sand may spill over the margin (Fig. 14), resulting in the superposition of amalgamated turbidites on thin-bedded turbidites (Figs 7 and 24). Scouring at the channel margin (Fig. 24) may form megaflutes, which have been preserved both within sets of amalgamated beds (Fig. 10) and on their uppermost surface (Figs 8 and 9). The two phases of the model account for the vertical succession observed in the packages without necessitating a kilometre or more of lateral migration. This model for the origin of thickening-upward packages will be referred to as the channel-spillover model

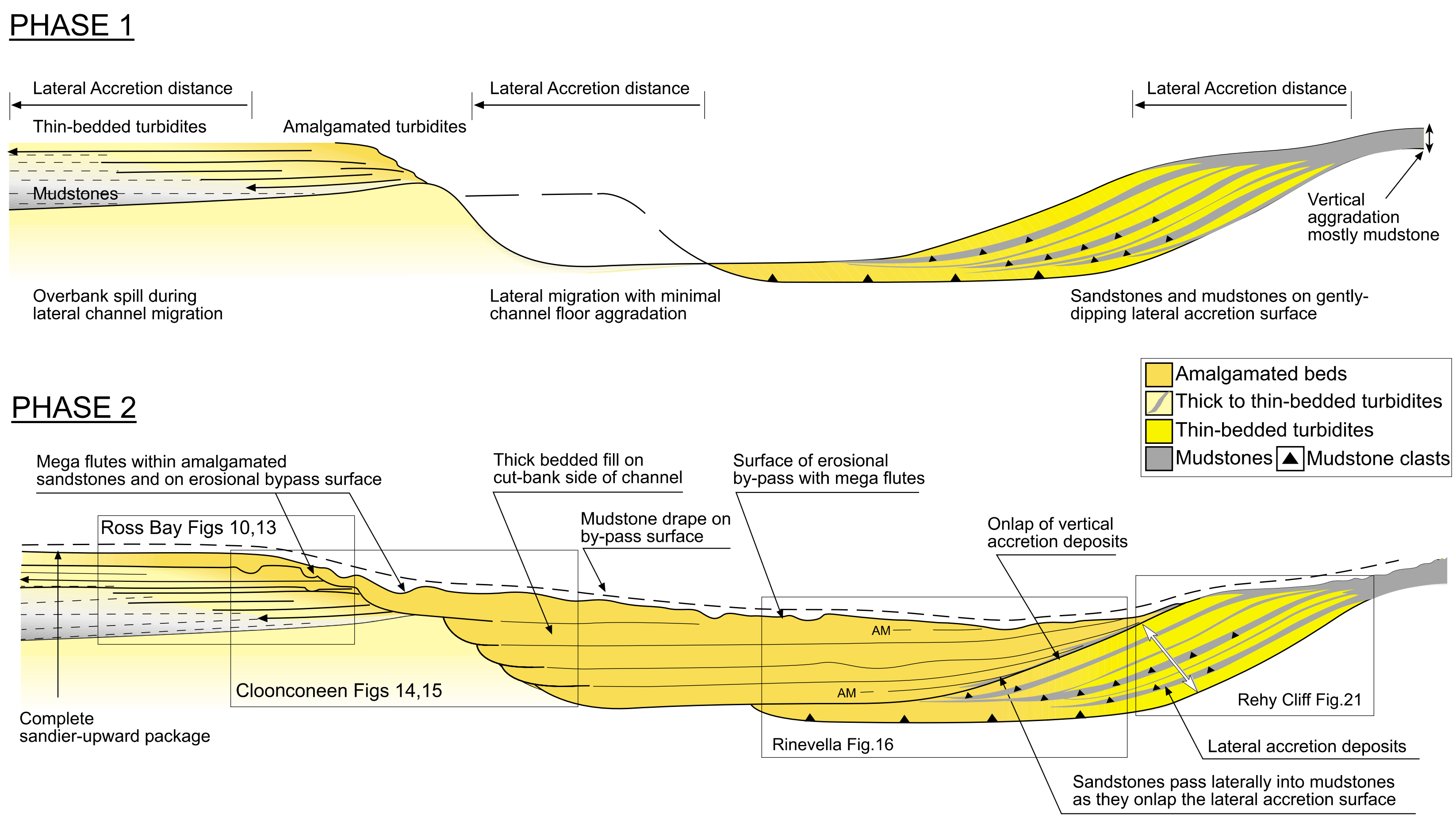


Fig. 24. Two-stage model of channel filling. Phase 1 shows lateral accretion, minimal aggradation and spill of mudstones and thin-bedded turbidites over the cut bank. Phase 2 shows vertical aggradation, with individual beds scouring into the cut bank, forming steps (Fig. 14). The fill consists of amalgamated sandstones. As the channel aggrades, scouring increases(megaflutes) and generates more spillover of thick-bedded amalgamated sandstones. The model is based on detailed observations, and boxes give figure references to the constituent parts of the model.

(Fig. 24). This figure shows where the individual 'pieces' have been observed (boxes in Phase 2 of Fig. 24). The best example of the complete Phase 2 diagram comes from the eastern channel at Rinevella (Fig. 14). Peakall *et al.* (2000) discussed a three-stage model of channel architecture, with a first stage of channel migration with preserved lateral accretion surfaces and a second stage of vertical channel aggradation where the channel also acts as a bypass zone. Stage three is the channel abandonment stage. Although the systems described by Peakall *et al.* (2000) are probably muddier than the Ross Formation, the first two stages of channel development also seem to be valid for the Ross Formation. The first stage of lateral accretion distance is suggested to be relatively short, and the vertical height of aggradation is low in the sand-rich Ross Formation.

In the context of a spillover model, it is possible that progressive loss of sand overbank results in progressively thinner and lower density flows downstream. This change in flow may be the trigger that leads to deposition in the channels, and the beginning of vertical aggradation and channel filling.

INTERPRETATION OF PALAEOFLOW IN THE PACKAGES

The packages at Kilbaha and Ross Bay have been analysed for palaeoflow, separating the data for (1) the thin-bedded turbidites and (2) the amalgamated sandstones (Fig. 22). Note that, in both areas, the directions for the thin-bedded turbidites are more widely spread, and the directions for the amalgamated sandstones are more closely clustered at the centre of the distribution.

Nevertheless, the vector means for both facies are essentially the same in each area. The amalgamated thick-bedded sandstones were interpreted above as having been deposited closest to the channel. If this is correct, their palaeoflow directions would more closely reflect those of the channel itself. The thin-bedded turbidites spread further from the channel and may be expected to have a wider fan of flow directions (Fig. 25).

At Ross Bay, directions for the amalgamated sandstones are concentrated in the 025° to 085° range, shown as the background grid in Fig. 25. The channel thalweg and postulated former thalweg positions have been superimposed on the

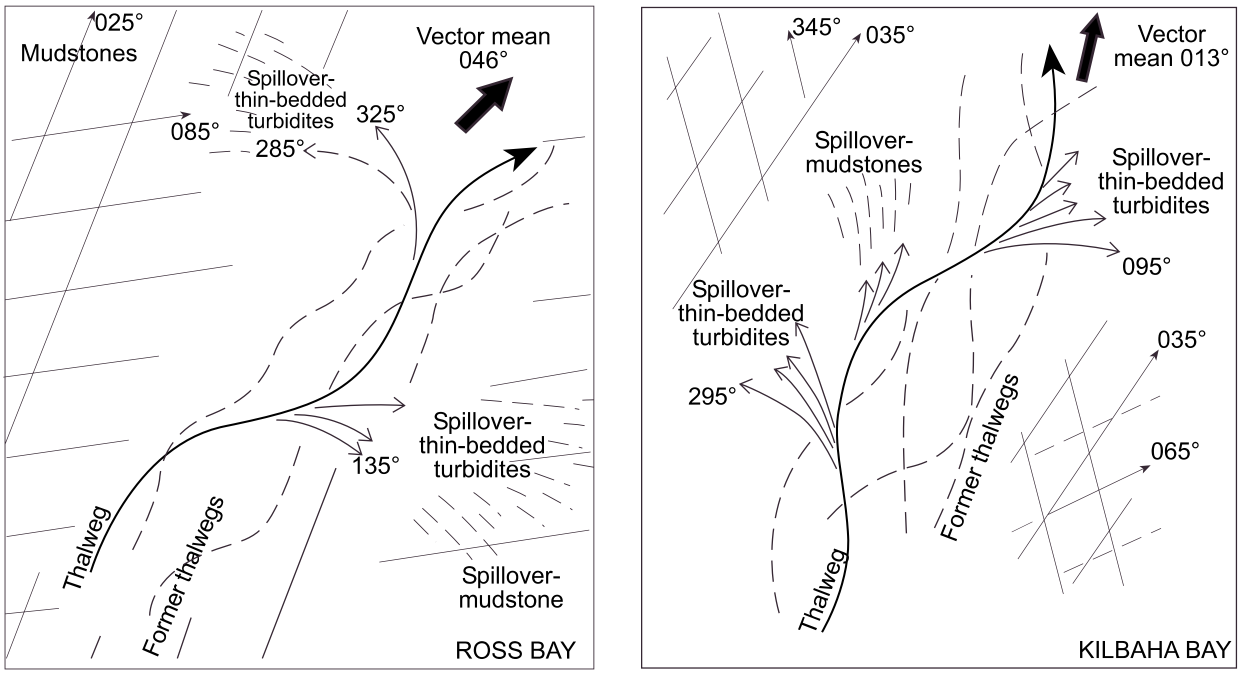


Fig. 25. Interpretation of palaeocurrent data (shown in histograms in Fig. 22) from packages at Ross Bay and Kilbaha. The background grid shows the range of flow directions associated with the data in the central part of the histogram for the amalgamated sandstone facies. It is assumed that the directions associated with this facies represent those of the channel thalweg and the most proximal overbank spill (Fig. 23). The thalweg and former thalweg positions are shown within this grid. The wider spread of directions associated with the thin-bedded turbidite facies represents increasing divergence of the overbank spill thin-bedded turbidites from the thalweg trend. The limits of the spill agree with the limits of data in the histograms (Fig. 22).

grid, with the channel sinuosity limited to the 025° to 085° range. The thin-bedded turbidites have the same vector mean, but a range of readings from 325° to 135° (with one reading at 285°). These directions are interpreted to represent spillover at channel bends (Fig. 25), with mudstones deposited even more distally than the thin-bedded turbidites. Note that the spillover diverges up to 50–60° on either side of the limits of channel sinuosity.

A similar diagram for Kilbaha Bay is shown in Fig. 25. The background grid shows flow directions for the amalgamated sandstones between 345° and 045° (perhaps 065°; see Fig. 22). Spillover of thin-bedded turbidites is from 295° to 095°, diverging about 50–60° on either side of the limits of channel sinuosity (the same relationship as at Ross Bay). Regardless of the local vector mean flow directions (010° at Kilbaha Bay and 046° at Ross Bay), the channels appear to be restricted to a range of about 50–60°. The channel length divided by the straight-line down-dip length, measured in Fig. 25, gives a low sinuosity of 1·12. The overbank spill of thin-bedded turbidites is limited to about 50–60° beyond the limits of channel sinuosity.

Channel and spillover relationships are shown in Fig. 23. Arrows indicate overbank spill at channel bends, and the megaflutes are interpreted as having formed by scouring at overspill locations. Implied facies relationships and flow directions have been discussed above. The sandbody geometry implied by this model is: (1) a low-sinuosity shoestring that formed as the channel filled by vertical aggradation; and (2) spillover lobes that alternate from side to side of the channel, and that generally become thinner bedded and muddier diagonally away from the channel. This model implies progressive loss of sand from the turbidity currents in the down-channel direction as a result of spillover. The channel itself may become shallower downstream, as suggested in Fig. 23, because of loss of sand and erosive power in the turbidity currents and construction of smaller spillover lobes.

CHANNEL BELTS

The various channel and sheet-like turbidite facies, and their palaeoflow directions, have been described up to this point. The thickening-upward packages have been suggested as being formed during the lateral migration, filling and ultimate avulsion of low-sinuosity channels. Superimposed on these relationships, there also appears to be a larger scale variation of palaeoflow directions associated with some of the channels and packages.

The first example of this larger scale pattern can be seen in the succession about 45–80 m below the *R. paucicrenulatum* marine band in Fig. 4, just below the postulated position of the *R. circumplicatile* marine band. Note particularly the 30–40 m thickness of section that includes Kilbaha Bay (Fig. 4). At this stratigraphic level, the Kilbaha channel and package flows are mostly northward, whereas the Toorkeal Bay packages flow north-eastward and, at Gull Island and Kilcredaun, the package flows are east- to south-eastward. The implication is that a stack of sinuous channels and related spillover packages at Kilbaha Bay all head roughly northwards, whereas a stack of packages at about the same stratigraphic level at Toorkeal Bay flow north-eastwards and at Gull Island and Kilcredaun head east- to south-eastwards. The channels and associated packages thus appear to lie within a persistent channel belt, which is also sinuous, as shown in the interpretation in Fig. 26, which shows the various channel and package palaeocurrent directions in their correct geographic positions. The overall vector mean flow direction (Fig. 3) has been added to show the basin axis.

A second example comes from the Bridges of Ross area, where the channels are at the same stratigraphic level but are younger than those at Kilbaha (Fig. 4). Figure 26 shows a channel trending north-west at Bridges of Ross and north-east at Fisherman's Point. These directions are based on field measurements discussed earlier and suggest a 90° bend in the channel system or two sinuous channels within the same channel belt with slightly different ages (Fig. 26).

An example of an upward change in palaeoflow, obtained from a lower stratigraphic level, is given by the northerly flow in channels at Rinevella that is then overlain by a north-eastward flow in channels at Clooncoween (Fig. 26).

Deposition further from channel belts

By restricting the channels to specific channel belts, with total aggraded thicknesses of 25–35 m, the question remains as to the style of deposition outside the belts. In Fig. 26, the proposed Kilbaha–Toorkeal Bay–Gull Island–Kilcredaun channel belt occurs in a 30 m thick section of the

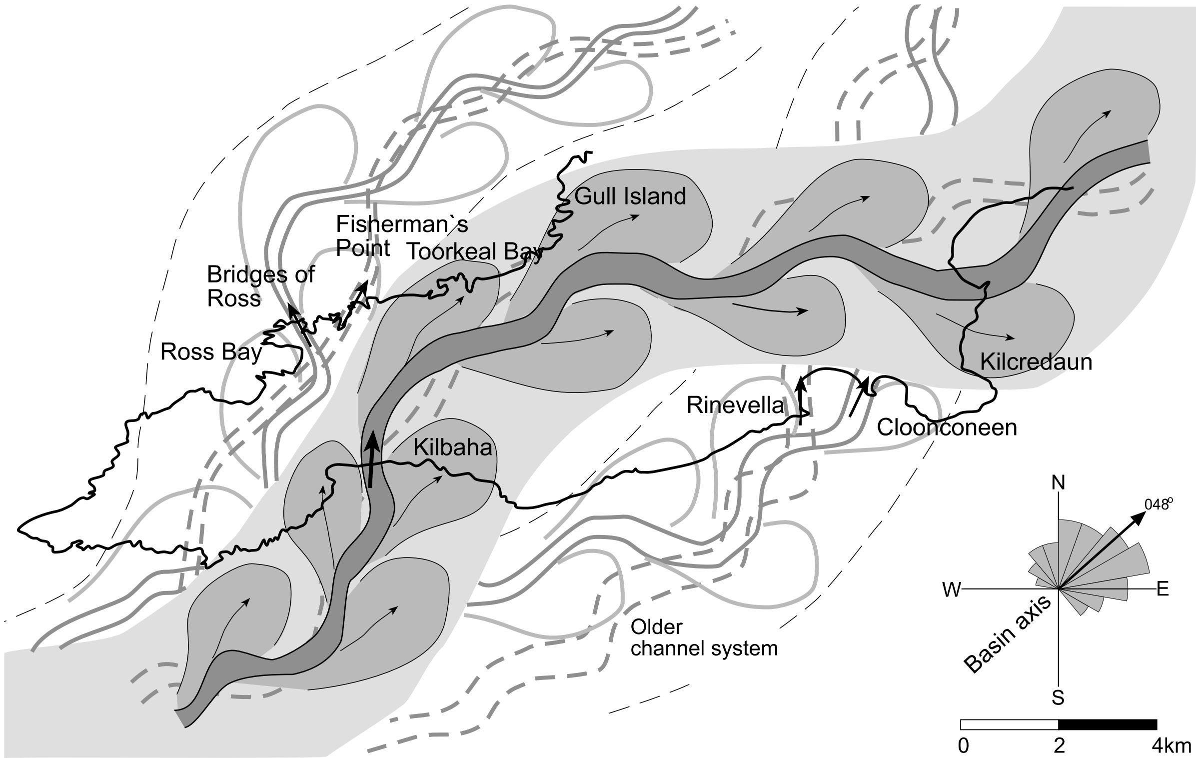


Fig. 26. Stacks of channels and packages at Kilbaha have northerly flow directions (palaeocurrent arrow within channel), whereas at the same stratigraphic interval (see text), they have north-easterly flow directions at Toorkeal Bay and east- to south-easterly flow at Gull Island and Kilcredaun. This can be interpreted in terms of sinuous channel belts, shown in dark grey (channels) and grey (overbank packages). Each channel has overbank spill lobes at channel bends; some, but not all, of these are shown. The palaeocurrent arrows for the spillover packages are constructed from field measurements. Note that, at a different stratigraphic interval (stippled lines), the sinuous channel belt model accommodates north-westward and north-eastward flow directions for channels at the Bridges of Ross and 'Fisherman's Point'. At yet another stratigraphic interval, the model accounts for northerly and north-easterly directions at Rinevella and Cloonconeen. The various locations are shown with reference to an outline of the Loop Head Peninsula, and the overall 048° palaeoflow direction for the Ross Formation is shown as the basin axis. In some of the stratigraphic sections (Fig. 4), prominent long-term trends in palaeoflow direction were shown (e.g. Fig. 27) and are interpreted to be the result of a gradual progressive downstream and lateral shift in the position of each sinuous channel that results in a gradual shift of the entire channel belt. Abrupt palaeoflow changes may result from avulsion and/or changes in relative sea level associated with marine bands and the development of new channel belts.

upper Ross Formation immediately below the *R. circumplicatile* marine band (Fig. 4). However, the equivalent section at Cloonconeen consists of unpackaged or poorly packaged mudstones and thin-bedded turbidites. It is therefore suggested that well-developed packages occur close (perhaps 1–2 km) to the channel belts and that, further from the belts, spillover results in random successions of unpackaged, finer grained beds. The degree of unpackaged successions would largely result from different distances to specific sinuous channels in the belt, as well as variations in the amount of sediment that spilled over at cut-bank and point-bar channel margins, which depends on factors such as the magnitude of turbidite flow or depth of channel.

VERTICAL CHANGES IN PALAEOFLOW DIRECTIONS

The depositional model has been developed without reference to long-term vertical trends in palaeoflow. Vertical changes in the Ballybunion section (Fig. 6) and similar trends from other sections must be interpreted in the light of the model developed. In analysing the trends, it appears useful: (1) to plot the raw data against their stratigraphic position; (2) to examine the raw data for trends and discontinuities; and (3) to average the flow directions using a three-bed moving average through the trends, but not across the discontinuities. These techniques have been applied at Ballybunion (Fig. 27), Ross Bay

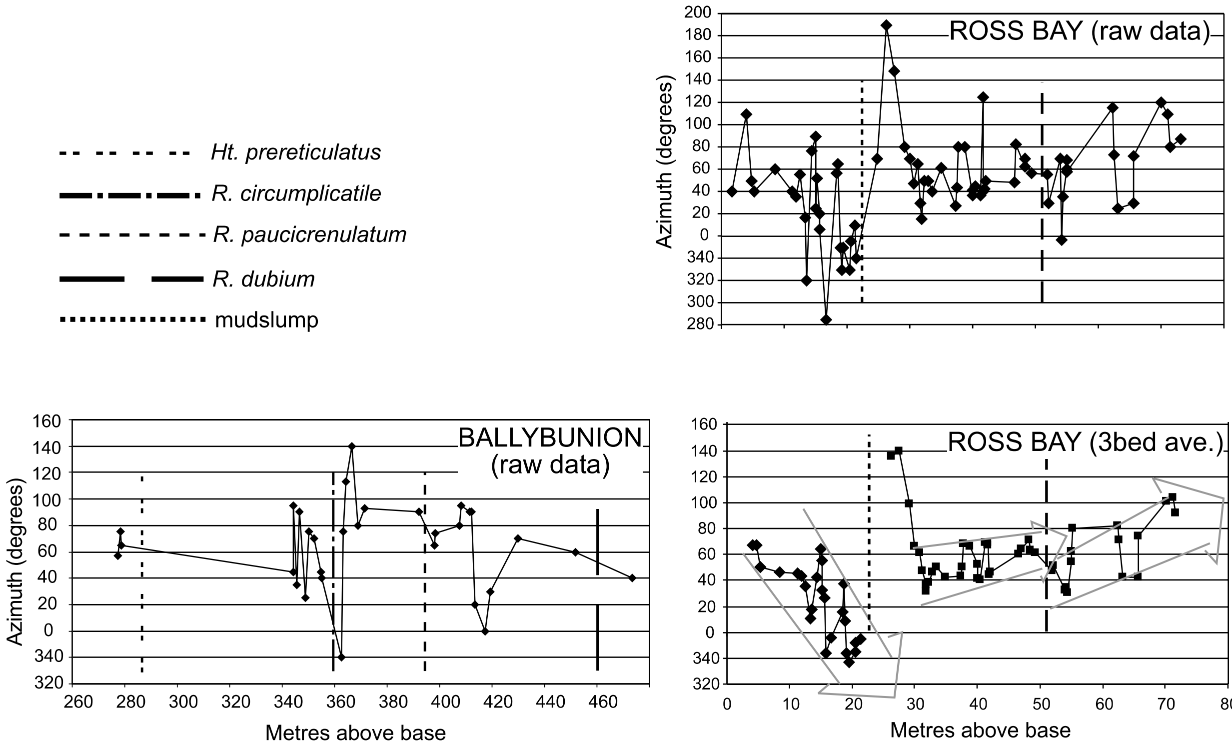


Fig. 27. Palaeocurrent data and three-bed moving average trends for Ballybunion and Ross Bay. At Ballybunion, 30 readings were taken in the upper part of the section. Flow directions appear to change abruptly across the inferred position of the *R. circumplicatile* marine band, but there are no long-term trends of palaeocurrent change. At Ross Bay, readings were taken on 74 beds. There is clearly a discontinuity at about 23 m, across the Ross Slide (Fig. 4), with one well-developed long-term trend below the slide and two trends above the slide (separated by the *R. paucicrenulatum*/*R. dubium* marine bands).

(Fig. 27), Kilcredaun Point (Fig. 28), Kilcloher Head (Fig. 28), Toorkeal Bay (Fig. 29), Gull Island (Fig. 29) and Clooconeen Point (Fig. 30). The major long-term trends in palaeocurrent change are shown with arrows, and the positions of marine bands, mudstone and slump horizons are also indicated.

Interpretation of vertical palaeoflow trends

The palaeocurrent data in Figs 6 and 27–30 show trends (grey arrows) with superimposed 'noise' and abrupt changes in palaeoflow between trends. In view of the model developed above, the 'noise' can be interpreted as resulting from channel sinuosity and overbank spill.

Progressive trends in palaeoflow

Progressive changes in flow direction are particularly well displayed at Ballybunion (Fig. 6), Ross Bay (Fig. 27), Kilcredaun Head (Fig. 28) and Toorkeal Bay (Fig. 29). The amount of change varies from 50° (upper trend at Ballybunion, Fig. 27) to 90° (lower trend at Ross Bay, Fig. 27). The trends may be caused by processes entirely contained within the channel system (autocyclic) or superimposed from outside (allocyclic).

The autocyclic interpretation is shown in the partly conceptual reconstruction of the sinuous channel belt (Fig. 26). It is suggested that progressive downstream and lateral shifts in position of each sinuous channel will result in a gradual shifting of the entire channel belt. Figure 26 also shows the proposed extent of well-developed packages for a distance of 1–2 km from the sinuous channel belt. The grey overbank packages pass laterally from amalgamated sandstones into thin-bedded turbidites. Beyond these packages are areas characterized by 'unsystematic spillover' – unpackaged to poorly packaged successions, in which almost random facies sequences result from shifts in individual sinuous channels and various styles and volumes of spillover at channel bends.

At Ballybunion, well-developed palaeoflow trends were defined in the lower Ross Formation (Fig. 6), where there are no packages or channel-

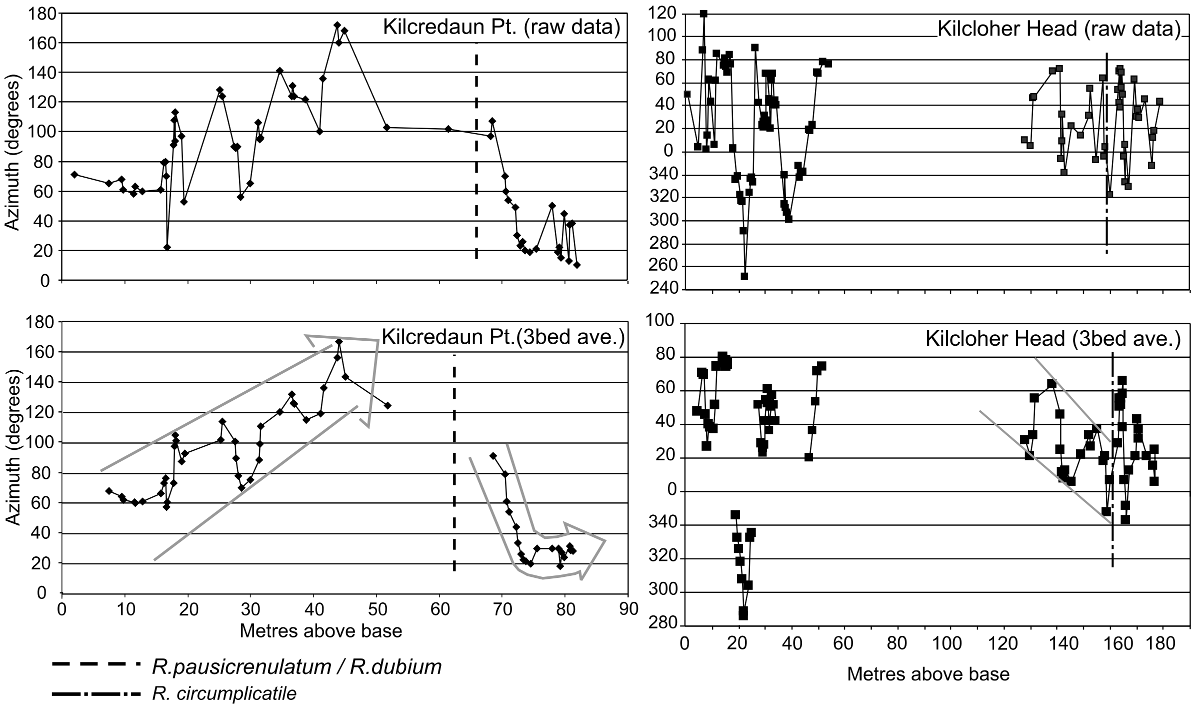


Fig. 28. Palaeocurrent data and three-bed moving average trends for Kilcredaun Point and Kilcloher Head. At Kilcredaun Point, 59 beds were measured. The three-bed moving averages reveal two long-term changes in palaeocurrent trends, one below and one above the *R. paucicrenulatum*/*R. dubium* marine bands. At Kilcloher Head, 104 beds were measured. The lower part of the section is characterized by 90° shifts in flow directions between groups of beds (north-east to north-west), with internal changes of 30–40° within each group. The data in the upper part (125–159 m) show a gradual change from 050° to 010°, but no trend can be seen above the inferred position of the *R. circumplicatile* marine band.

fill deposits. The model can be used to explain these trends autocyclically by proposing that the trends reflect progressive changes in flow directions on a smooth unchannellized basin floor, influenced by the shifting mouths of sinuous channels further upstream. The vertical trends in palaeoflow might also be interpreted allocyclically, such as through gradual tectonic tilting of the basin floor. If this were the case, the flow trends in all sections (Fig. 4) should be roughly the same at any stratigraphic level. This is clearly not the case, except immediately above the *R. dubium* marine band, where an 'easterly swinging to northerly' trend has been documented at Ross Bay, Gull Island, Clooncconeen and Kilcredaun (Fig. 4). For all the Ross Formation below the *R. paucicrenulatum* marine band, an autocyclic interpretation is therefore favoured.

Abrupt changes in palaeoflow trend

Abrupt changes across marine bands are seen at Ballybunion (about 65 m, Figs 6 and 27; and at 358 m, Fig. 27), possibly at Ross Bay (51 m, Fig. 27), Kilcloher Head (160 m, Fig. 28), Kilcredaun Head (62 m, Fig. 28), Gull Island (38 m and 84 m, Fig. 29) and Clooncconeen Point (113 m, Fig. 30). One likely interpretation is that the sea-level changes required for the development of marine bands (Collinson *et al.*, 1991) also involved the shifting of channel patterns and the abrupt superimposition of a new channel belt on top of an older one with a different flow direction. This is shown in Fig. 26, where younger channel belts overlie older systems (stippled) at high angles, illustrating avulsion and re-establishment of channel belts across marine bands.

Abrupt changes in palaeoflow direction are also associated with thick mudstone horizons (Ross Bay, 24 m, Fig. 27) and slump/slide horizons (minor changes at Toorkeal Bay, 20 m, Fig. 29). At Toorkeal, flows were consistently in the 040–080° range below the slump, but become part of a progressive change above the slump, with a shift from about 050° to 130°. It could be argued that channel avulsions resulted in diversion of turbidity currents to other parts of the basin floor, with mudstone deposition and changes in flow direction as a consequence of avulsion. Alternatively, tectonic movements may have triggered slumps and locally blocked and diverted some of

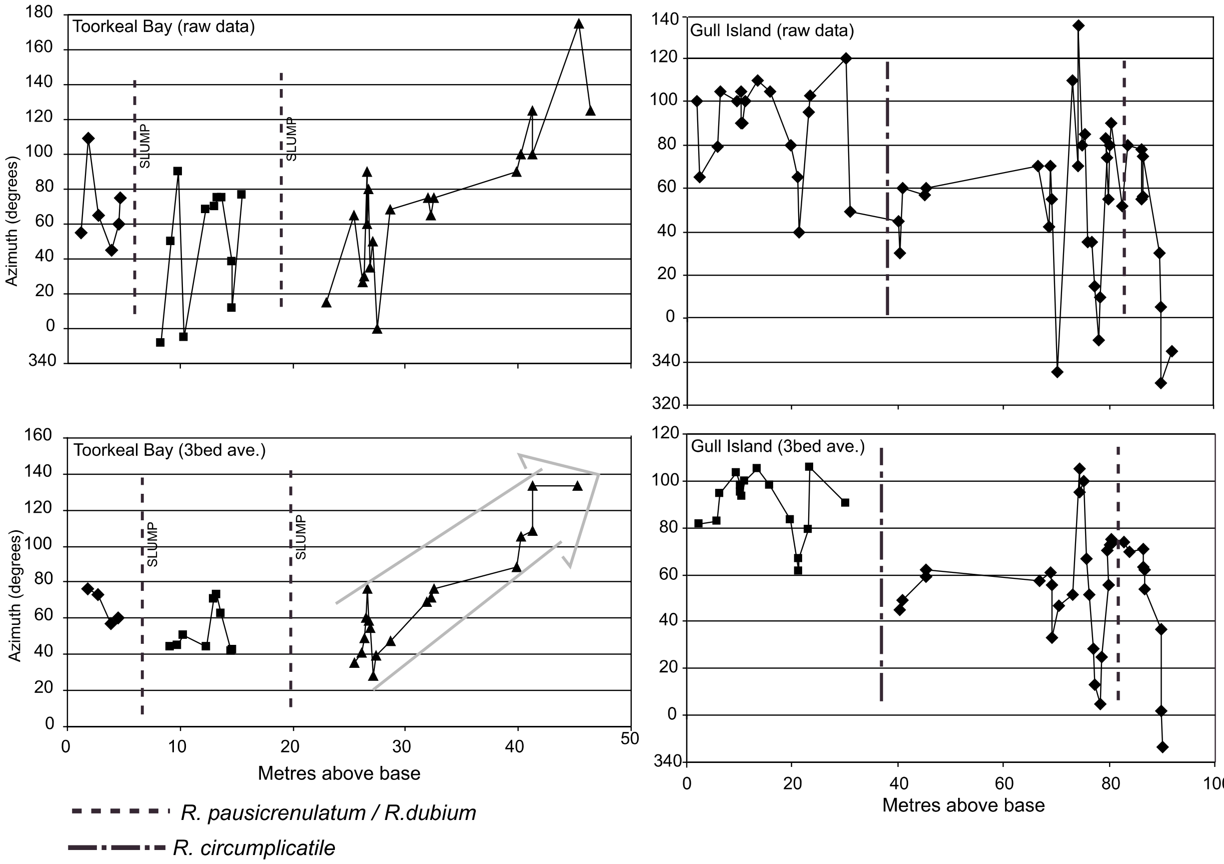


Fig. 29. Palaeocurrent data and three-bed moving average trends for Toorkeal Bay and Gull Island. At Toorkeal Bay, 37 beds were measured. There may be discontinuities across the slumped horizons, and there is a definite trend in the upper 25 m of the section. At Gull Island, 52 beds were measured. There appear to be two groups of data, separated by the *R. circumplicatile* marine band, but no long-term trends in palaeoflow directions are apparent.

the channels, as has been documented on the Rhone Fan (Droz & Bellaiche, 1985).

CONCLUSIONS

1 The Upper Carboniferous Ross Formation in County Clare, western Ireland, can be divided into lower and upper parts. The lower Ross Formation is characterized by extensive tabular turbidites with no channels and no small-scale thinning- or thickening-upward successions. Channels, thickening-upward packages (2–4 m scale) and slump/slide horizons characterize the upper Ross Formation.

2 Channels are up to 100 m wide and have fills 5–10 m thick. Facies relationships suggest that channel filling began with deposition of lateral accretion deposits on the 'point bar' of the channel, with simultaneous erosion on the 'cut-bank' side and overbank spill of mud and thin turbidites at the cut-bank side. There was then a phase of vertical accretion, with deposition of thick amalgamated sandstones. As the channel filled, more and more sand spilled overbank, particularly on the cut-bank side, forming channel-margin thick-bedded sandstones with megaflutes. These beds can be traced laterally from the channels into the thick amalgamated turbidites that form the upper parts of packages.

3 Upper Ross Formation packages consist, from base to top, of mudstones, thin-bedded turbidites, thick-bedded amalgamated turbidites and a sharp uppermost surface that is commonly scoured and displays megaflutes. Palaeoflow directions associated with the thick-bedded turbidites have a much smaller range than those associated with the thin-bedded turbidites. Although the megaflutes are prominent on the upper scoured surfaces, they also occur within the thick-bedded amalgamated turbidites. This implies that the megaflutes are related to scouring at channel margins, rather than forming from single, large, channel-initiating flows. These packages are

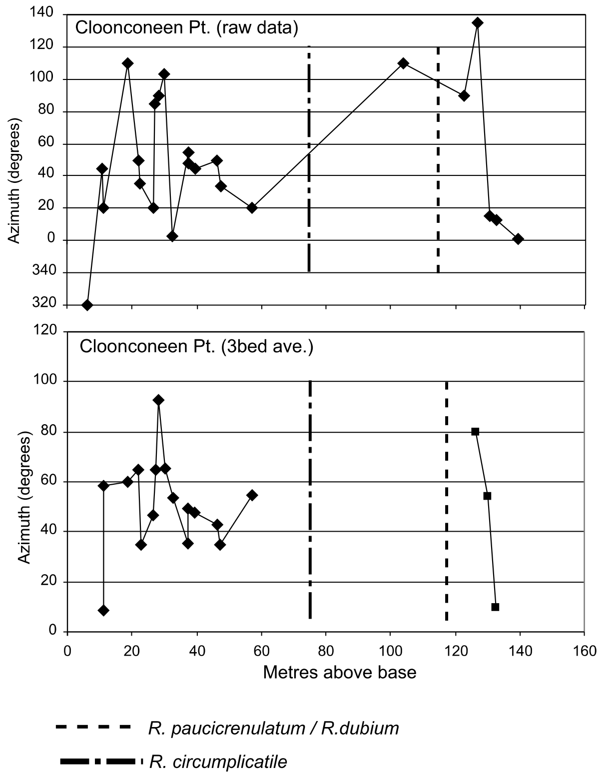


Fig. 30. Palaeocurrent data and three-bed moving average trends for Clonconeen Point. Readings were taken on 23 beds. No long-term trends can be seen.

interpreted to have formed during progressive lateral shifting of the channels.

4 At certain correlative stratigraphic intervals about 30 m thick, flows may be geographically variable, for example consistently northward at Kilbaha Bay but consistently north-eastward at Toorkeal Bay and east- to south-eastward at Gull Island and Kilcredaun Point. Within the 30 m interval, a stack of four or five channels and/or packages may exist. This suggests a persistent tendency for flows to head northwards or eastwards through this stratigraphic interval, thus defining a sinuous channel belt composed of stacked individual channels and packages.

5 It is concluded that, on the largest architectural scale, the upper Ross Formation consists of sinuous channel belts with poorly packaged or unpackaged turbidites beyond the edges of the belts. An individual channel belt may aggrade a few tens of metres before local avulsion or channel reorganization closer to the source shifts the channel belt to a new position. A channel belt consists of a stack of about four or five individual channels with their spillover lobes (packages). The channels are about 100 m wide, or perhaps up to 200 m allowing for lateral accretion, and the packages are 1–2 km wide. It follows that an individual channel-package system may be a little over 4 km wide, and the stack of such channels may form a channel belt of the order of 5 km wide.

6 The Ross Formation is unusually well exposed and can be reconstructed in three dimensions. The reconstruction suggests that it should form an excellent outcrop analogue for sandy, low-sinuosity channel systems with sandy spillover deposits but no large muddy levees.

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