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Stratigraphy and sedimentary evolution of a modern macro-tidal incised valley: An analogue for reservoir facies and architecture

CLAIRE MCGHEE*, DAHIRU MUHAMMED†, NABOTH SIMON†, SANEM ACIKALIN*, JAMES E. P. UTLEY†, JOSHUA GRIFFITHS†,‡, LUKE WOOLDRIDGE†,‡, IRIS T. E. VERHAGEN†, CEES VAN DER LAND* and RICHARD H. WORDEN†

**School of Natural and Environmental Sciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK (E-mail: C.A.Mcghee2@newcastle.ac.uk)*

†School of Environmental Sciences, University of Liverpool, Liverpool, L69 3BP, UK

‡BP Exploration, Chertsey Road, Ashford, Feltham, Sunbury-on-Thames, Middlesex, TW16 7LN, UK

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ABSTRACT

Incised valley fills are complex as they correspond to multiple sea-level cycles which makes interpretation and correlation of stratigraphic surfaces fraught with uncertainty. Despite numerous studies of the stratigraphy of incised valley fills, few have focused on extensive core coverage linked to high fidelity dating in a macro-tidal, tide-dominated setting. For this study nineteen sediment cores were drilled through the Holocene succession of the macro-tidal Ravenglass Estuary in north-west England, UK. A facies and stratigraphic model of the Ravenglass incised valley complex was constructed, to understand the lateral and vertical stacking patterns relative to the sea-level changes. The Ravenglass Estuary formed in five main stages. First, incision by rivers (*ca* 11 500 to *ca* 10 500 yrs BP) cutting through the shelf during lowstand, which was a period of fluvial dominance. Secondly, a rapid transgression and landward migration of the shoreline (10 500 to 6000 yrs BP). Wave action was dominant, promoting spit formation. The third stage was a highstand at *ca* 6000 to *ca* 5000 yrs BP, creating maximum accommodation and the majority of backfilling. The spits narrowed the inlet and dampened wave action. The fourth stage was caused by a minor fall of sea level (*ca* 5000 to *ca* 226 yrs BP), which forced the system to shift basinward. The fifth and final stage (226 yrs BP to present) involved the backfilling of the River Irt, southward migration of the northerly (Drigg) spit and merging of the River Irt with the Rivers Esk and Mite. The final stage was synchronous with the development of the central basin. As an analogue for ancient and deeply buried sandstones, most of the estuarine sedimentation occurred after transgression, of which the coarsest and cleanest sands are found in the tidal inlet, on the foreshore and within in-channel tidal bars. The best-connected (up to 1 km) reservoir-equivalent sands belong to the more stable channels.

Keywords Connectivity, estuary, incised-valley, Ravenglass, sandstone reservoir quality, sequence stratigraphy, tide-dominated.

INTRODUCTION

Incised valleys form as a result of basinward migration of the shoreline, inducing exposure of the shelf and promoting enhanced fluvial incision within the lower reaches of the coastal valleys. The valley fills during landward migration of the shoreline and contains the most complete record of lowstand, transgression and subsequent highstand deposition (Zaitlin *et al.*, 1994). The stratigraphic expression of the deposits within the valley can promote sediment preservation that can result in highly economical oil and gas reservoirs and storage sites for carbon dioxide for CCS (Carbon Capture and Storage) projects (Salem *et al.*, 2005; Hein, 2015; Wang *et al.*, 2019; Meng *et al.*, 2020). The understanding of reservoir facies and stratigraphic architecture of incised valley-fills is also critical for predicting a field's recoverable hydrocarbon potential (Hampson *et al.*, 1999; Slatt, 2013; Wang *et al.*, 2019) and reducing overall risk. The valley deposits are unique in that they represent the creation of accommodation space by one process (migration of shoreline) and the infill by a range of processes (wave, tide and fluvial; Boyd *et al.*, 2011). In many modern and ancient examples of incised valleys, the sediment fill is typically composed of coarse-grained fluvial and alluvial beds at the valley base. Subsequent transgression and sea-level highstand result in estuarine and marine sedimentation, of which the former appears to be the most common volumetrically (Allen & Posamentier, 1993; Willis & Gabel, 2001; Garrison & Bergh, 2006; Chaumillon *et al.*, 2010). Estuarine sedimentation within the valley is complex in that the deposits are the product of river, tide and wave action causing a tripartite zonation of facies that corresponds to net bedload transport (Boyd *et al.*, 2011). Compound filling (corresponding to multiple phases of sea-level cycles) of such valleys results in complex architecture, resulting in extensive amalgamation of stratigraphic surfaces (Zaitlin *et al.*, 1994). Widely adopted conceptual facies models and stratigraphic frameworks have been developed to explain and predict the distribution of sediment within incised valleys during transgression (Dalrymple *et al.*, 1992a; Allen & Posamentier, 1993; Zaitlin *et al.*, 1994; Heap *et al.*, 2004). A recent study by Wang & *et al.* (2020) demonstrated that 87 Quaternary incised valley fills showed similar stratigraphic organization comparable to the classic conceptual models (Dalrymple *et al.*, 1992b; Allen & Posamentier, 1993; Zaitlin *et al.*, 1994; Heap *et al.*, 2004; Virolle *et al.*, 2019) but displayed significant variability in the stratigraphic architecture of valley fills, related to continental margin type, inherited topography, river size, catchment area and shoreline hydrodynamics. Depending on the dominant hydrodynamics at the estuary mouth, two end-members have been recognized (Dalrymple *et al.*, 1992a). Wave-dominated estuaries are typically described as possessing a tripartite zonation of facies; a barrier spit at the estuarine mouth, tidal inlet, a sheltered muddy central basin and a bayhead delta. In tide-dominated systems, the marine sand body is made up of elongate tidal bars in the inlet and the mouth. The meandering channel belt in tide-dominated settings is the equivalent to the central basin in the wave-dominated models. Typically, the inner estuarine facies above the sequence boundary in wave-dominated settings can be very muddy compared to sandy facies in the tide-dominated settings.

Despite a vast amount of literature regarding the stratigraphy of incised valley fills, few have focused on high resolution core coverage coupled with high fidelity dating within a macro-tidal tide-dominated setting. The Cobequid Bay–Salmon River estuary, located in the Bay of Fundy (Tessier, 2012), is arguably one of the most cited modern examples of a tide-dominated valley fill (Dalrymple & Zaitlin, 1994) and represents the basis for the Dalrymple *et al.* (1992a) classic conceptual model. The Gironde Estuary in France is also another commonly cited tide-dominated valley fill (Allen & Posamentier, 1993; Fenies & Tastet, 1998; Virolle *et al.*, 2019). Ravenglass is a scaled down version of many modern estuaries discussed in the literature, covering an area of 5.6 km^2 (Chaumillon *et al.*, 2010a; Menier *et al.*, 2010). The Gironde Estuary (south-west France) and the tide-dominated palaeo-Changjiang in China have drainage basins that cover approximately 75 000 km^2 (Allen & Posamentier, 1993) and 1.8×10^6 km^2 (Hori *et al.*, 2001), respectively. Despite differences in scale and sediment supply, the three estuaries possess similar morphologies.

The lateral and vertical stacking patterns of the Holocene deposits of the Ravenglass Estuary, north-west England, UK were investigated, in order to model facies distributions within a tide-dominated incised valley. According to Zaitlin *et al.* (1994), the deposits have formed a single, simple-fill in that most of the deposits correspond to one cycle of sea-level fall and rise during the Holocene (Lloyd *et al.*, 2013). The

Ravenglass incised valley is a relatively small, modern day macro-tidal estuary with a multi-tributary system that has undergone extensive interpretation of the surface and shallow subsurface sediment (Griffiths *et al.*, 2018; Wooldridge *et al.*, 2018, 2019). Here, the study will examine the complete sedimentary in-fill of the Ravenglass valley, produce detailed facies descriptions and create high resolution correlations linking shoreline migration to style of sedimentation.

This study aims to address the following research questions, in order to summarize the evolution of the Ravenglass Estuary incised valley-fill:

1 What is the stratigraphic organization of infill for the Ravenglass Estuary?

2 What are the architectural elements of the infill for the Ravenglass Estuary?

3 What is the morpho-sedimentary evolution of the valley?

4 Is lateral and vertical correlation of facies possible over 100 to 1000 m scales?

5 How does the Ravenglass incised valley-fill compare to current stratigraphic models?

GEOLOGICAL SETTING AND HYDRODYNAMICS

The Ravenglass Estuary is located in Cumbria, England (Fig. 1A), west of the Lake District mountains (maximum elevation of 980 m at Scafell Pike). It is one of the most natural and least

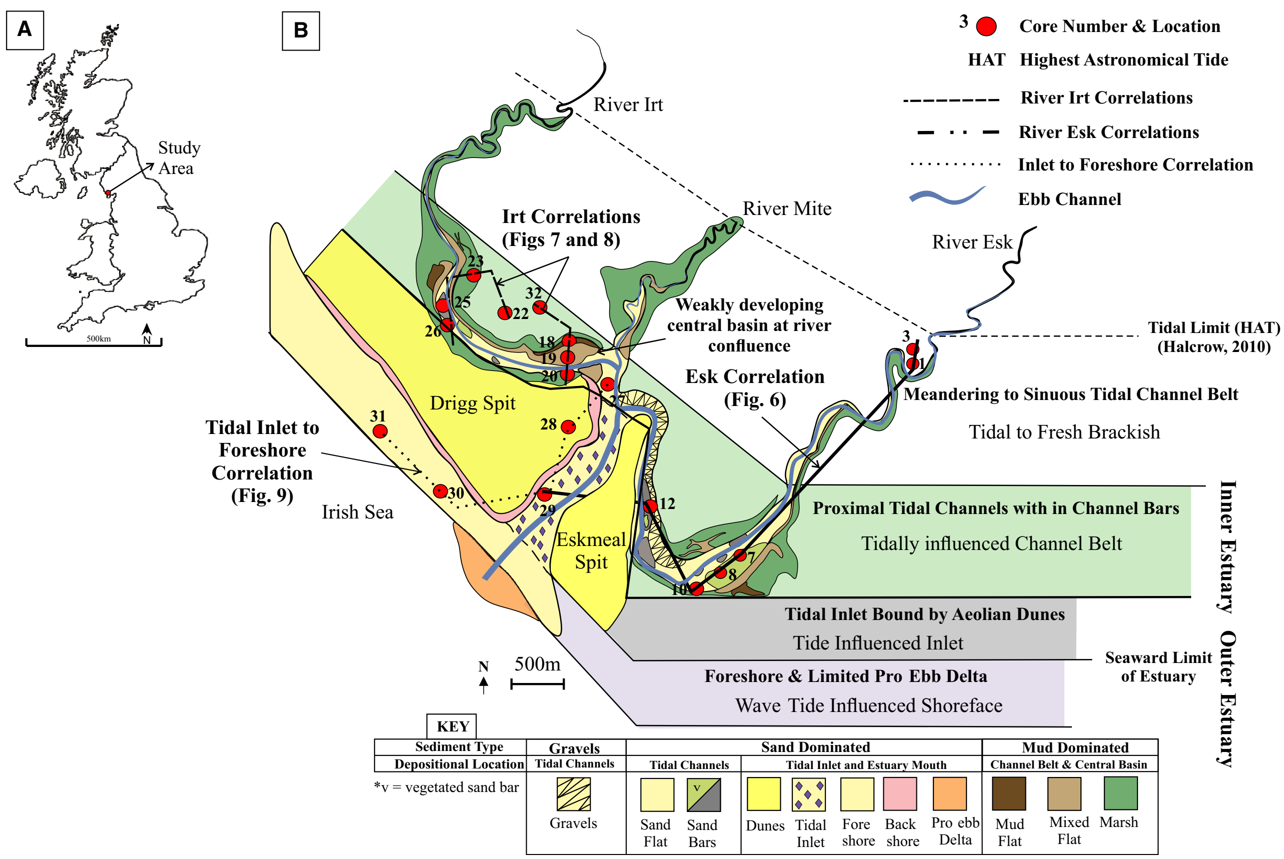


Fig. 1. (A) Location map indicating Ravenglass Estuary, Cumbria, UK with a red circle. (B) The present-day estuarine zones of Ravenglass Estuary. The outer estuary (purple and green) is defined by the landward limit of the tidal inlet (dashed line). The outer estuary consists of a tidal inlet bound by the Drigg and Eskmeal spits (grey) and a pro-ebb delta (purple). The inner estuary consists of proximal tidal channels (the rivers Irt, Esk and Mite) with a distal meandering tidal channel belt (green) and proximal tidal sand bars (yellow). The map also indicates the position of the 19 Holocene cores (red circles) used in the study. Correlation panels for the Holocene cores are shown by a single dashed line for the River Irt, dashed and dotted line for the River Esk and a dotted line for the tidal inlet to foreshore.

developed estuaries in the UK, with little industry and virtually no artificial coastal defences. The estuary lies on relatively flat low-lying coastal plain, occupying an area of 5.6 km^2, of which approximately 80% is intertidal (Bousher, 1999; Lloyd *et al.*, 2013; Wooldridge *et al.*, 2017a; Griffiths *et al.*, 2018, 2019; Wooldridge *et al.*, 2018). The estuary is a mixed energy, macrotidal system with a mean spring tidal range of >7 m, leaving the estuary nearly fully drained at low tide. The estuary is fed by three main rivers, the Irt, Mite and Esk. The River Irt flows at 3.4 m^3/s^{-1} and the River Mite flows at 0.4 m^3/s^{-1} (Bousher, 1999) The River Esk has an average flow rate of 4.2 m^3/s^{-1} (broadly similar to the River Irt) with suspended sediment concentrations of 20 to 70 g m^{-3} during spring tides and 5 to 20 g m^{-3} during neap tides (Assinder *et al.*, 1985). These westward-draining rivers cut through the steep hinterland topography of the English Lake District and meet at a point of confluence creating a single tidal channel (Fig. 1B). Restriction in the tidal inlet size can be attributed to the formation of the Drigg barrier spit to the north-west and the Eskmeal barrier spit to the south-east (Fig. 1B). Strong tidal asymmetry occurs due to the shallow bathymetric nature and short length of the estuary (Kelly *et al.*, 1991). Modern surface facies from the Ravenglass Estuary consist of gravel, tidal flats, fluvial tidal bars (alternate bars) and dunes, tidal-inlet, backshore, foreshore and pro-ebb delta (Wooldridge *et al.*, 2017b; Griffiths *et al.*, 2018; Simon *et al.*, 2021).

The Ravenglass Estuary is underlain to the west of the Lake District Boundary Fault by Triassic Sherwood Group sandstones, and to the east by Devonian Eskdale Granites, Ordovician Borrowdale Volcanics and the Cambrian Skiddaw Group. The River Irt drains Borrowdale Volcanic Group andesites and Sherwood sandstones whereas the River Esk drains the Eskdale granite and granodiorite. The minor River Mite drains Eskdale granite and granodiorite and Borrowdale volcanic rocks.

QUATERNARY GEOLOGY

Western Cumbria has been affected by periodic Quaternary glacial advance and retreat (Merritt & Auton, 2000; Royd, 2002), with the most recent event occurring during the Mid to Late Devensian (MLD), between 28 000 and 13 000 yrs BP (Moseley, 1978). During the MLD, Ravenglass lay in an ice-sheet convergence zone, fed by ice from both Scotland to the north and the Lake District to the east. Ice flow directions have been interpreted from the distribution of erratics (granite and greywackes from the Southern Uplands of Scotland) and drumlin orientation, which support the interpretation of Scottish Ice impinging on the Cumbrian coastline (Merritt & Auton, 2000). The evolution of the Cumbrian coastline and resulting sediment deposits have been greatly modified by post-glacial processes and changes in relative sea level linked to spatially variable glacio-isostatic rebound (Zong & Tooley, 1996). According to the lithostratigraphic and biostratigraphy study of central Cumbria, and specifically Ravenglass, the area underwent a sea-level highstand of approximately +2.3 m Ordnance Datum (OD) during the Late Devensian between 17 000 and 15 000 yrs BP. From 15 000 to 11 500 yrs BP, a rapid fall in sea level below −5 m OD (modelled up to −30 m) occurred as glacio-isostatic rebound exceeded global sea-level rise. After the period of incision, a rapid marine transgression began in the Early Holocene between 11 500 and 6000 yrs BP, followed by a stabilized highstand, estimated at +2 m OD with a gradual fall until present (Lloyd *et al.*, 2013; Fig. 2).

SAMPLES AND METHODS

To construct a facies architecture model of the Ravenglass Estuary Holocene sedimentary sequence, information on the age and depositional environments of the sediments was investigated. To do this, radiocarbon dating and detailed core descriptions from 19 cores were undertaken.

Core acquisition

Nineteen cores were drilled through the Holocene succession as far as the Ravenglass Glacial Till Member (RGTM), under tender by Geotechnical Engineering Limited. All sites were subject to an initial desk study to estimate depth to glacial till based on previous reports and publications (Assinder *et al.*, 1985; Kershaw *et al.*, 1990; Halcrow Group, 2013; Coast & Area, 2015). All sites were subject to environmental impact assessment in conjunction with Natural England; several sites in, and around, the estuary required the presence of an independent ecologist to ensure there was no damage to protected species, such as natterjack toads and great

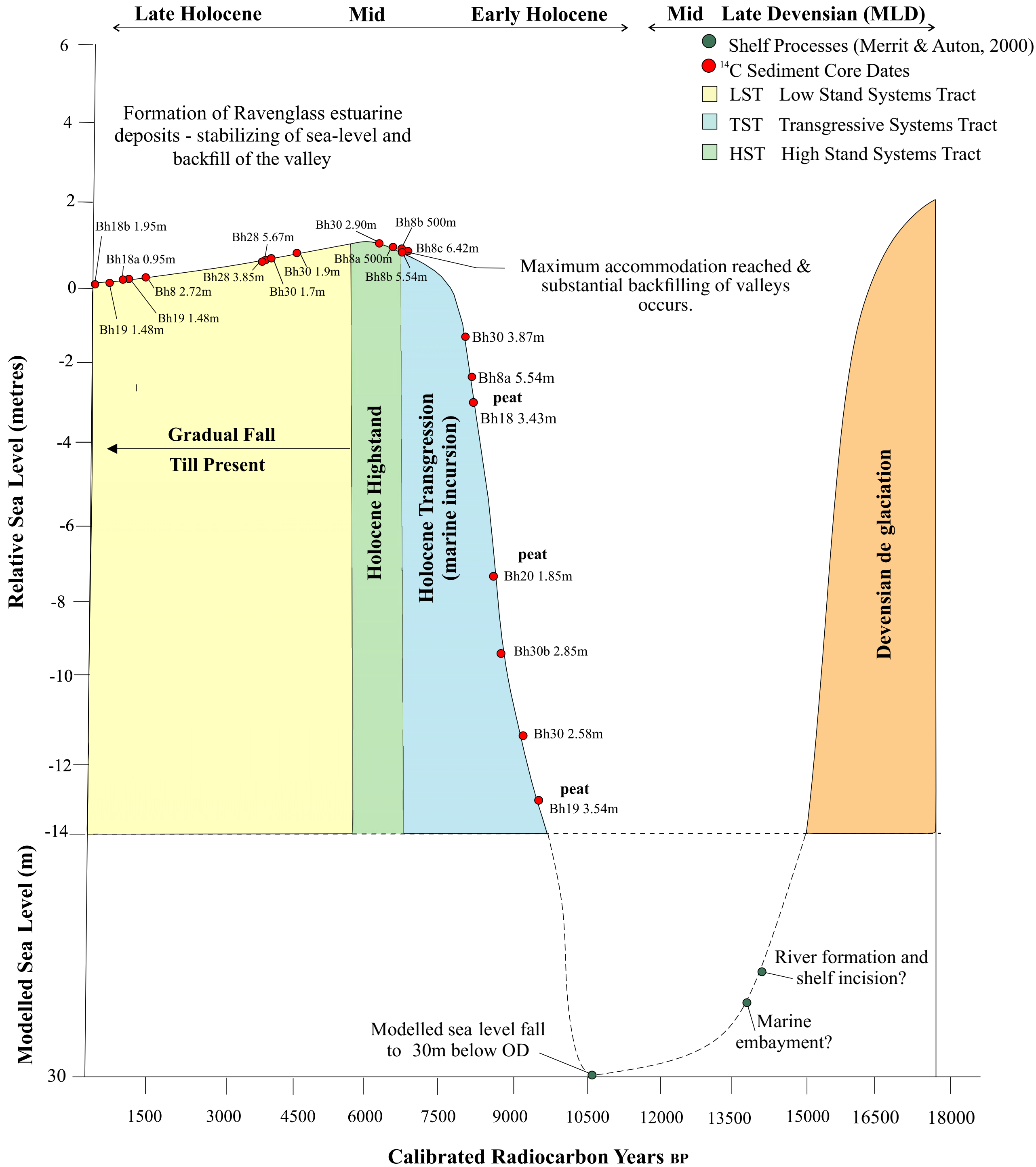


Fig. 2. Lloyd *et al.* (2013) Devensian–Holocene sea-level curve with all new ^{14}C dates and depths plotted from Ravenglass Estuary cores (red circles). The Devensian glacial lowstand, when isostatic rebound outstripped sea-level rise, between 12 000 and 10 500 yrs BP inducing enhanced fluvial incision in the lower valleys. This was followed by a rapid transgression, which was characterized by a phase of relative sea-level rise, occurring between *ca* 10 500 and 6000 yrs BP During this time, net sediment transport was landward. A minor fall in relative sea level from 5000 yrs BP to the present day, resulting in dominant estuarine conditions (adapted from Lloyd *et al.*, 2013).

crested newts. Due to more than 100 years of weapons testing from the Ministry of Defence-owned Eskmeals firing range (located on the southern spit with heavy-artillery firing out into the East Irish Sea) much of the beach and tidal inlet was flagged as high-risk for unexploded ordnance (UXO). The risk of UXO was mitigated by Lankelma Limited who appraised each foreshore and pro-ebb delta site with a magnetometer probe mounted on a wide-tracked vehicle (Fig. 3D) immediately before coring. Core acquisition had to be timed around periods of low tide and at least two cores were collected at each site. Cores were acquired using either a Geotechnical 'P60' Rotary rig or a Geotechnical 'Pioneer' rotary rig. The Pioneer rig is a lightweight percussion rig that was used on soft substrates, such as mudflats (Fig. 3C) and vegetated tidal bars (Fig. 3A). The P60 is a heavier rotary rig which was used on hard substrates such as

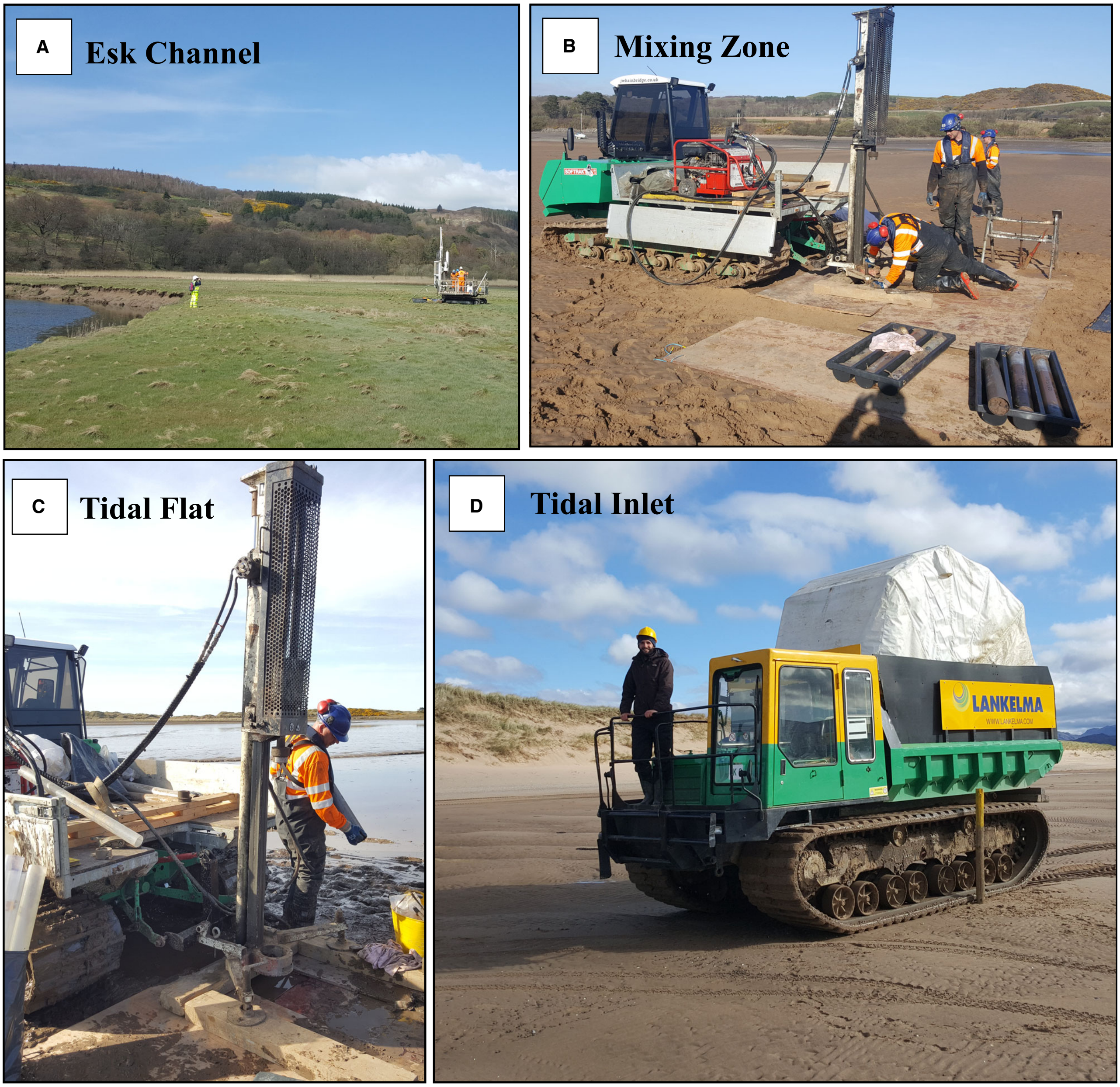


Fig. 3. Drilling locations and rigs used to core the Ravenglass valley-fill. (A) River Esk tidal channel with Pioneer (B) mixing zone of the rivers (C) tidal flat and (D) tidal inlet. People for scale are *ca* 1.8 m tall.

sandflats (Fig. 3B) and in areas of uneven land surface, such as the upper reaches of the Esk Estuary flood plain, because it is capable of operating on slopes of up to 45°. The retrieved cores were 12 cm in diameter retained in a semi-rigid plastic liner and transported back to the University of Liverpool for subsequent analysis.

Core descriptions

The 19 sediment cores were sliced and photographed wet, and after air-drying. Detailed logging of each core was undertaken, wet and then dry, at a scale of 1 : 5. Facies were described in terms of grain size, sorting, colour, sedimentary structures, bed thickness, presence of roots and shell fragments, bioturbation index and type of bioturbation.

Radiocarbon dating (^{14}C)

Nineteen radiocarbon analyses were undertaken under contract by the Chrono Centre, which is part of Queen's University of Belfast, in Northern Ireland, UK. Samples of shell fragments and organic matter were taken from the cores as they were logged. The precise depth and type of material was carefully recorded (Table 1).

Table 1. Radiocarbon dating results, showing the samples for each facies association (FA), as well as sediment descriptions, sample depth (m), ^{14}C ages and the associated error (±). RGTM = Ravenglass Glacial Till Member.

FA	Sample type	Sediment context	Depth (m)	^{14}C ages	±
RGTM	Nil	Nil	Nil	Nil	Nil
Alluvial Gravels	Nil	No ^{14}C datable material	Nil	Nil	Nil
Peats	Peat fragments	Central basin peat beds overlying glacial till. Local depressions with no in-channel deposition	3.54 1.85 3.43	**9309** **8416** **8094**	38 37 32
Tidal–Fluvial	Thin white bivalve shells	Medium to coarse-grained, moderately sorted sands with shell fragments. Signifies the first sediment deposited within the valley	5.00 5.54	**6971** **6566** **7948**	30 40
Aeolian Dunes	Medium white bivalve shell fragments	Fine to medium-grained sediment with rare pebbles and shells	3.85 5.67	**3910** **4341**	24 26
Tidal Meander and Central Basin	Oyster and thin white bivalve shells	Fine-grained, poorly sorted sand and mud. Restricted to central basin samples. Upper 1 m of sediment contaminated from Sellafield, a nearby nuclear power plant	1.46 1.48 1.55 1.95	**813** **733** **634** **123**	20 21 26 24
Tidal Sand Bar	Thin white bivalve shells	Medium-grained sands, moderate to well-sorted with shelly horizons	2.72	**1229**	20
Foreshore	White bivalves and blue oyster shells	Fine to medium-grained sand with thicker gravel beds. Located between the Irt and Esk palaeo-channels and potentially a zone of tidal ravinement	2.58 2.90 1.91 1.91 1.70 1.49	**9003** **6439** **3629** **3727** **3307** **1890**	–
Salt and Fresh Marsh	Nil	Nil	–	Nil	Nil
Upper Flow Regime	Nil	Nil	–	Nil	Nil

The shell fragments used for dating were identified as bivalves, such as oysters. Shells were classified as being thin or thick specimens. It was recognized that thick samples may have been able to withstand erosion from their initial site of deposition, followed by subsequent re-deposition; thick-shelled samples are therefore more liable to anomalous ages than thin-shelled samples. Organic matter subject to dating included leaf-bearing peat.

Samples from the top 1 m of sediment were not subject to radiocarbon dating since they were considered to be at risk of contamination from radionuclides, including ^{14}C, released accidentally from the Sellafield (previously known as Windscale) nuclear reprocessing site, 15 km north of Ravenglass, since its inception in 1947.

POST-GLACIAL PALAEO-TOPOGRAPHY

All available data related to the depth of the RGTM throughout the Ravenglass Estuary are collated in Fig. 4. Data from cores published by Merritt & Auton (2000) and a core from the British Geological Survey (BGS, 1939, http://mapapps2.bgs.ac.uk/geoindex/home.html?layer=BGSBoreholes&_ga=2.138148784.1233529240.1629361412-464657529.1629361412) data repository were also plotted on the palaeo-topographical map. The map further incorporates glacial till outcrop locality information from Ravenglass (Griffiths *et al.*, 2019). Based on the 28 spot depths to glacial till, a tentative palaeo-topographical map of the Ravenglass area has been drafted, prior to the valley being infilled (Fig. 4).

The palaeo-Irt, in the north-west of the area, had a steep north-west-side with a relief of *ca* 22 m. South-east of palaeo-Irt, the land surface rose up, by *ca* 12 m, with a local 'high' in the area currently occupied by the central basin of the present-day estuary (Fig. 4). On this basis, the palaeo-Irt flowed directly into the Irish Sea rather than deviating to the south-east and joining the palaeo-Esk. The initial separation of the palaeo-Irt from the palaeo-Esk is supported by historical map information that shows that the Irt only merged with the Esk at approximately 270 yrs BP. A map by Speed from the year 1610 ME (Speed, 1610) shows the Irt flowed directly into the Irish Sea, while a map by Thomas Donald from the year 1774 ME (Donald, 1774) shows that the estuary had adopted the current geomorphology with the River Irt deviating to the south-east and joining the Rivers Esk and Mite.

Based on the mapped contours to the glacial till, the palaeo-Esk followed the outline of the present-day River Esk, in that it deviated to the north-west and joined the much smaller River Mite (Fig. 4). It was previously suggested that the palaeo-Esk flowed directly into the Irish Sea (Halcrow Group, 2013) but there seems to be no evidence to support this interpretation. Moreover, there is archaeological evidence [signs of a Neolithic flint napping factory, possibly as old as 9000 yrs BP; (Bonsall *et al.*, 1989; Clare *et al.*, 2001)] proving the existence of the Eskmeals spit immediately after the glacial retreat, supporting our interpretation of the trajectory of the palaeo-Esk.

FACIES ANALYSIS AND INTERPRETATION

In this section, results are presented from field observations, aerial photography, core analysis in the form of sedimentary logs, facies characterization and radiocarbon dating, in order to assess the infill of the incised valley and to establish whether correlation over hundreds to thousands of metres is possible. This work also aims to build on the surface and 1 m core studies by Wooldridge *et al.* (2018).

The total thickness of the post-glacial sedimentary infill for Ravenglass Estuary is up to 9 m, close to the estuary mouth, thins to the east (landward) to between 4 m and 6 m in the cores (Figs 6, 7, 8 and 9). A total of nine facies were identified in the core and are illustrated in Fig. 4 and listed in Table 2.

Ravenglass Glacial Till Member (Seascale Glaciogenic Formation) (Inner and Outer Estuary)

The RGTM underlies the majority of the Ravenglass Estuary and is present in all cores except 18 and 27 (Figs 4 and 7). The till forms part of the Seascale Glaciogenic Formation (Merritt & Auton, 2000). The grey-brown, stiff, matrix-supported, silty clay represents the lowest part of the stratigraphy in many of the cores and also crops out as knolls throughout the estuary. The till is poorly sorted and displays a chaotic structure with rare sedimentary and meta-sedimentary clasts and rare shell fragments. The till varies in thickness across the estuary based on core data (between 0.2 m and 1.0 m) and shows a sharp contact with the overlying facies. The distribution of glacial till within the valley is probably a

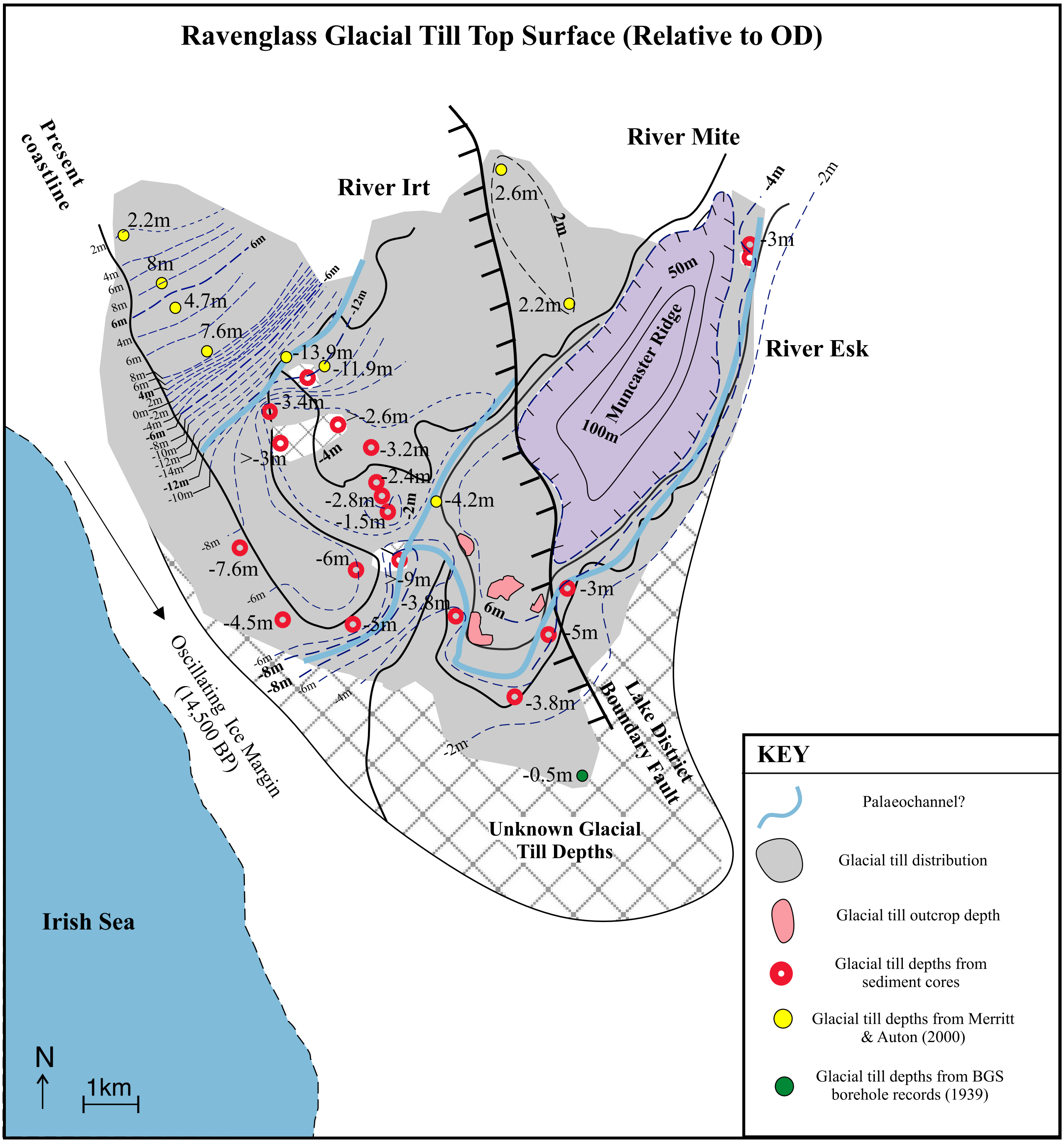


Fig. 4. Contoured surface map of the Ravenglass Glacial Till Member (RGTM) based on outcrop data (pink), the drilled sediment cores (red circles), data from Merritt & Auton (2000; yellow) and the BGS repository (green). The white squared box under the present-day Eskmeal Spit is unknown depths to the RGTM. The blue lines indicate the palaeo-channels of the River Irt, Mite and Esk. Note the steep sided, deeper channel of the River Irt to the north-west and the topographical high between the River Irt and River Mite. The river Esk flows around an Ordovician Granitic fell (purple) known as Muncaster Ridge, bound by the Lake District Boundary Fault.

product of the movement of meltwaters from the retreating and advancing ice-sheets to the north/north-west, that focused around the Esk and present-day foreshore (Delaney, 2003). It has been suggested that the tills are a result of proglacial lakes fed by glacial meltwaters during the

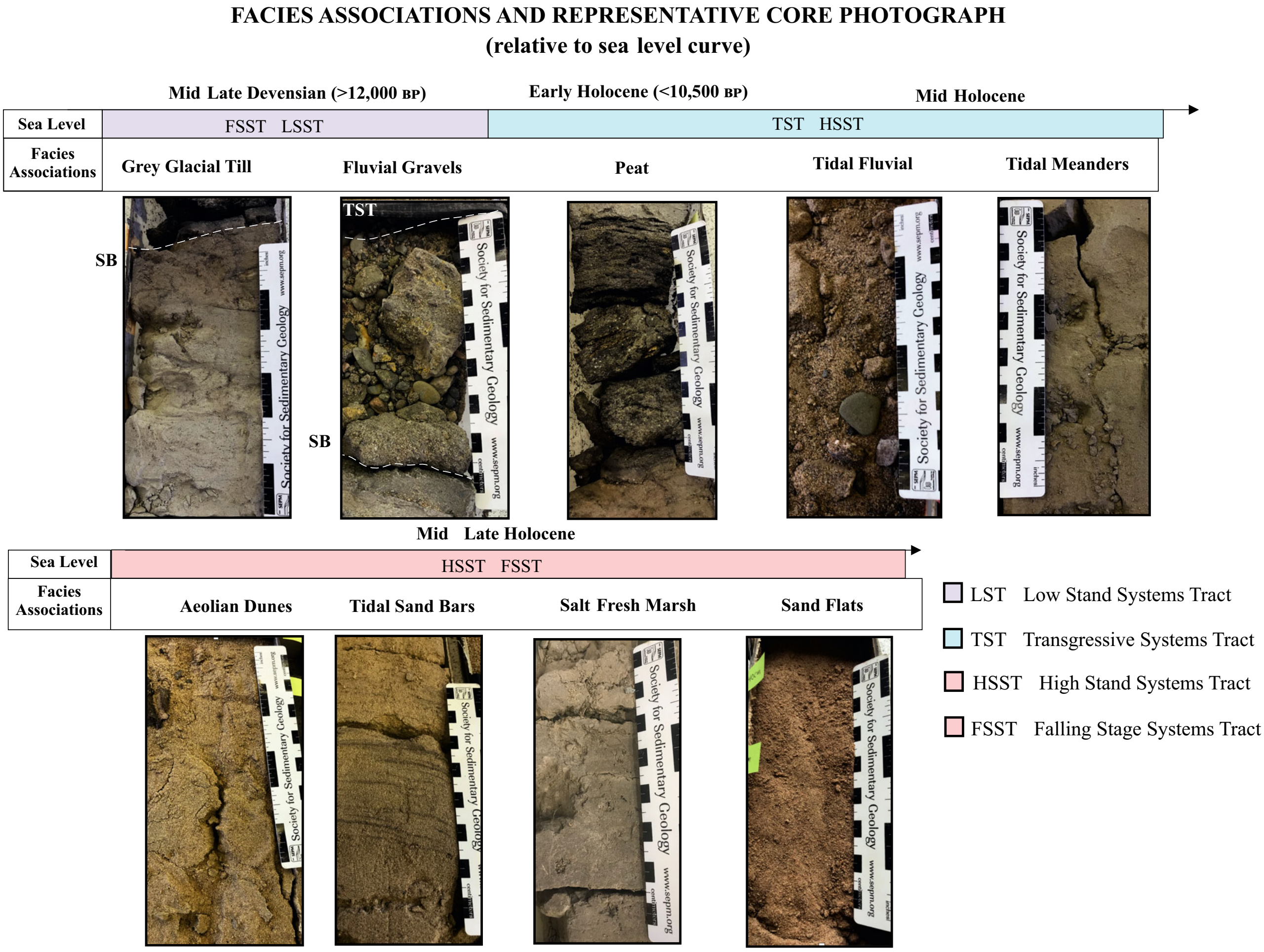


Fig. 5. Facies associations (FA) and representative core photograph. From left to right (top to bottom): The Devensian RGTM, a grey diamicton till that is a poorly sorted with a chaotic internal structure. The fluvial gravels composed of gravel grade material and coarse sand. The laminated black to brown coloured peat is composed of leafy organic material. The tidal fluvial sands are composed of medium to coarse-grained sand with pebbles and disarticulated shell fragments. The aeolian dunes are composed of fine to medium-grained cross-bedded sands. The tidal meanders are fine to medium-grained, interbedded muds and sands that fine upward. The tidal sand bars show an overall fining upward profile from coarse-grained sands to interbedded muds and sand. Vegetated tidal sand bars are commonly capped with salt or fresh marsh. The marsh is composed of interbedded silt and mud which is often moderately bioturbated and roots are present near the top. The sand flats are fine-grained with some disarticulated shell fragments.

Main–Late Devensian (MLD; Merritt & Auton, 2000). The older, Late Devensian ('late glacial') set of tills, which occur sporadically around the Cumbrian coast, were formed during, and shortly after, retreat of MLD ice. The top of the RGTM represents the sequence boundary.

Alluvial gravel and coarse sands

The gravel and coarse sands (cores 1, 3, 12, 27, 28 and 31; Figs 6, 7 and 9) commonly overlie the RGTM and vary in thickness (0.6 to 3.0 m). The gravels and coarse sands can be correlated over distances of 0.5 km in the outer estuary (Fig. 9). The clasts range from 3 to 7 cm in size, are angular to sub-angular and are sedimentary, meta-sedimentary and igneous, suggesting that the source is predominantly from the catchment area. Poor sorting, angularity and the absence of shell fragments suggest that the gravels are of fluvial–alluvial origin. Radiocarbon dating was not possible due to the absence of shells and peat. The occurrence of gravel beds beneath the estuarine deposits implies that a fluvial–alluvial system extended *ca* 15 to 20 km further west (seaward) than the present-day coastline. Merritt & Auton

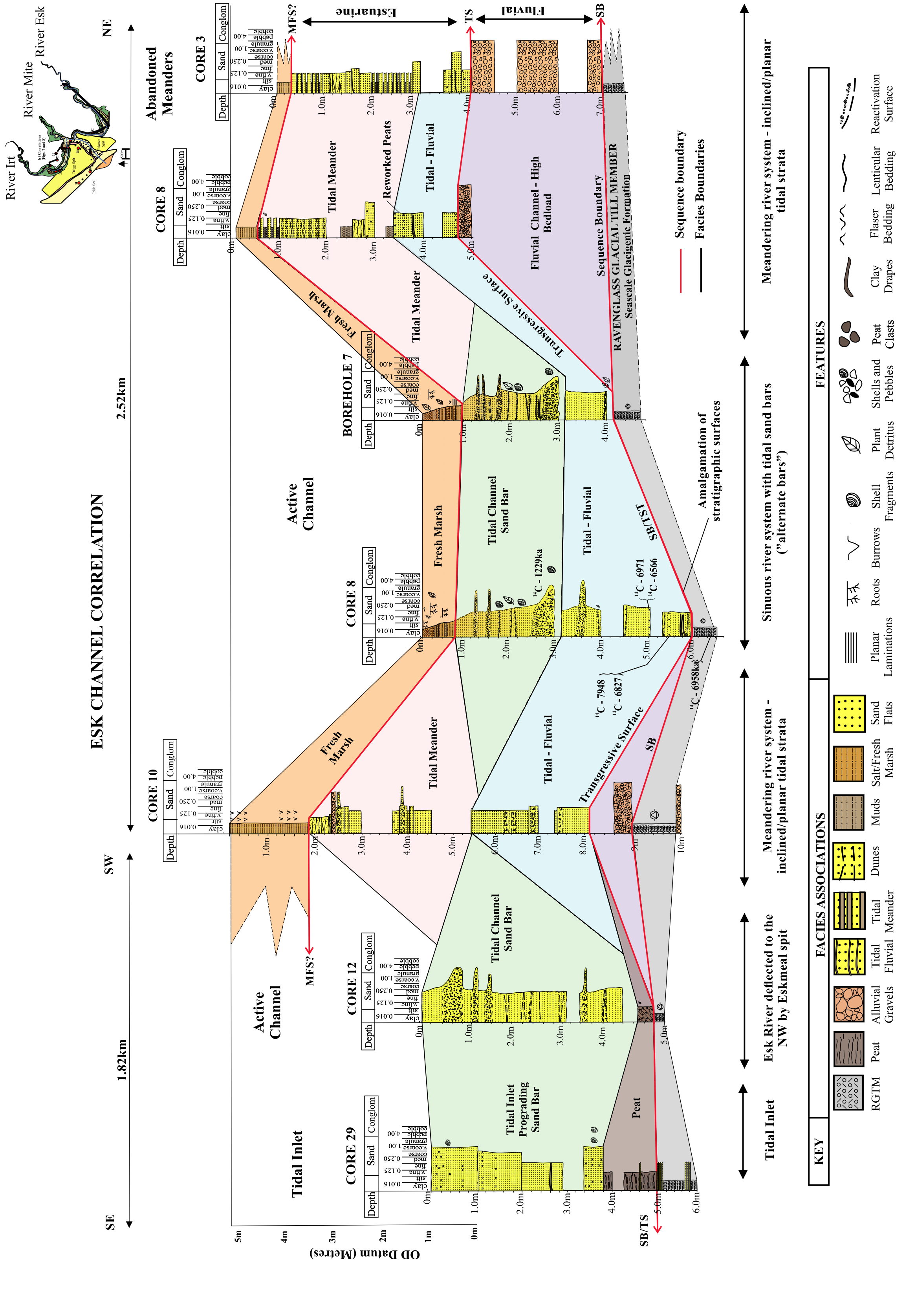


Fig. 6. River Esk correlation panel from the Devensian to present-day highlighting inner estuarine facies and sequence stratigraphic boundaries marked by the dashed black lines. The red dashed lines highlight uncertainties in the correlation, especially associated with the tidal meander sediments. Also highlighted is the meandering–sinuous–meander nature of the sediment with channel tidal bars (alternate bars) and upstream point-bars, indicative of tide-dominated systems.

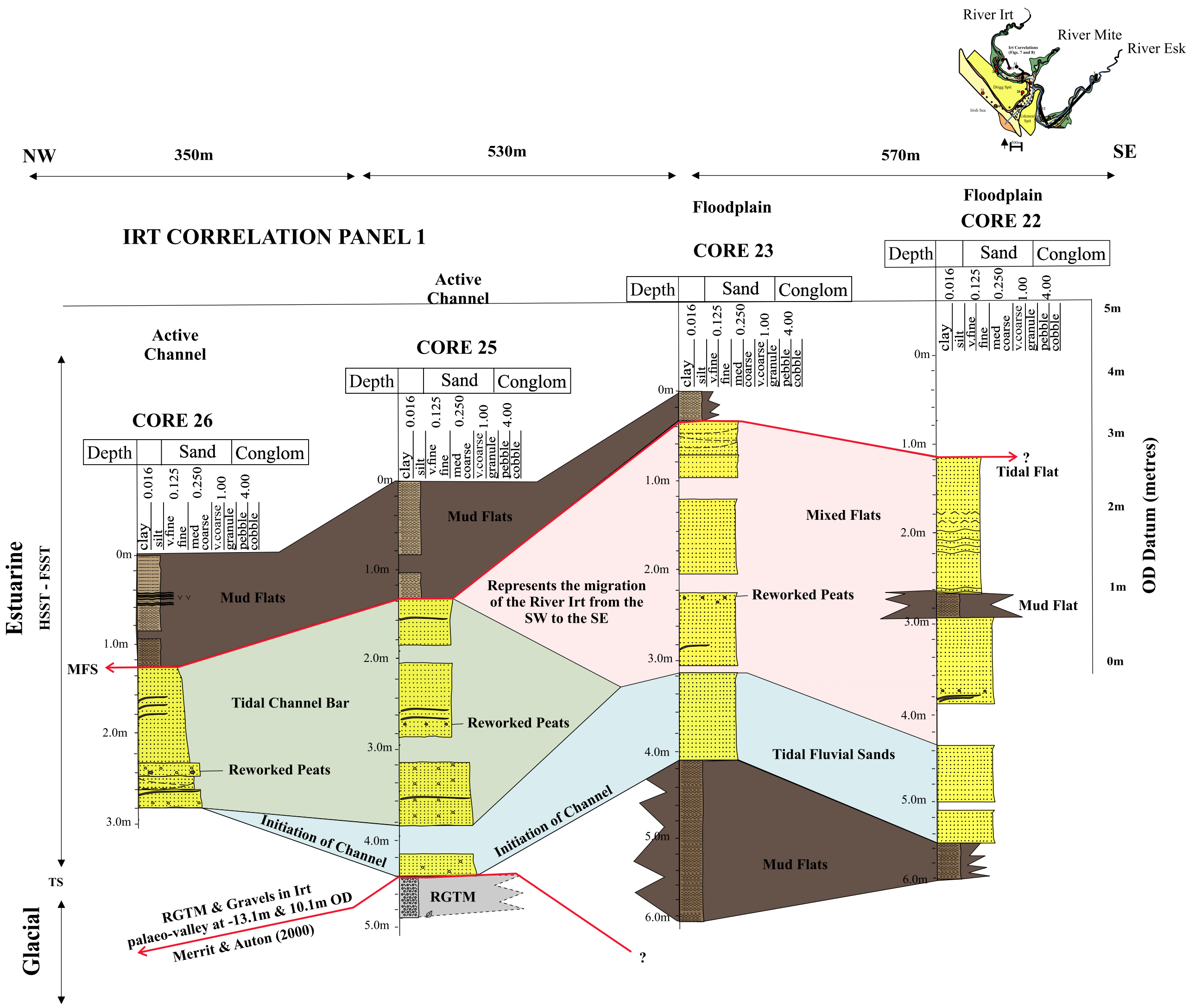


Fig. 7. River Irt correlation panel 1. The River Irt panel shows the inner estuarine facies and sequence boundaries marked by the solid red lines. Note the lack of sequence boundaries with the exception of core 25 which has the RGTM. Above the RGTM are fluvial tidal bars between core 25 and 26, channel sands and mud flats in cores 22 and 23. The sequence boundary is located deeper in the Irt palaeo-channel at 13.1 m (OD) indicated by the red arrow (Merritt & Auton, 2000).

(2000) have suggested a relative sea-level fall of −30 m below ordnance datum at *ca* 10 200 yrs BP which could have resulted in the deposition of the gravels. The base of the fluvial gravels represents the sequence boundary within the valley.

Estuarine brown–black peats

Brown–black peat (cores 12, 18, 19, 20, 29 and 32; Figs 6, 8 and 9) is rich in indistinct, probably deciduous, leaves and other woody plant material and is likely terrestrial in origin. It also contains some silt and is well-consolidated. Peat thickness varies across the estuary between 0.1 m and 1.3 m (Figs 7, 8 and 9). Peat occurs directly on top of the glacial till at sites where fluvial–alluvial gravel and coarse sands are absent. In the inner estuary, the peats can be correlated over distances of 0.5 km but are commonly laterally discontinuous. This facies typically displays a sharp contact with the overlying estuarine sands and underlying till or gravel and is mostly concentrated in the central basin and in the Esk channel.

As shown by the radiocarbon dating, the peat beds are the oldest Holocene sediments from the valley-fill that can be dated, since the

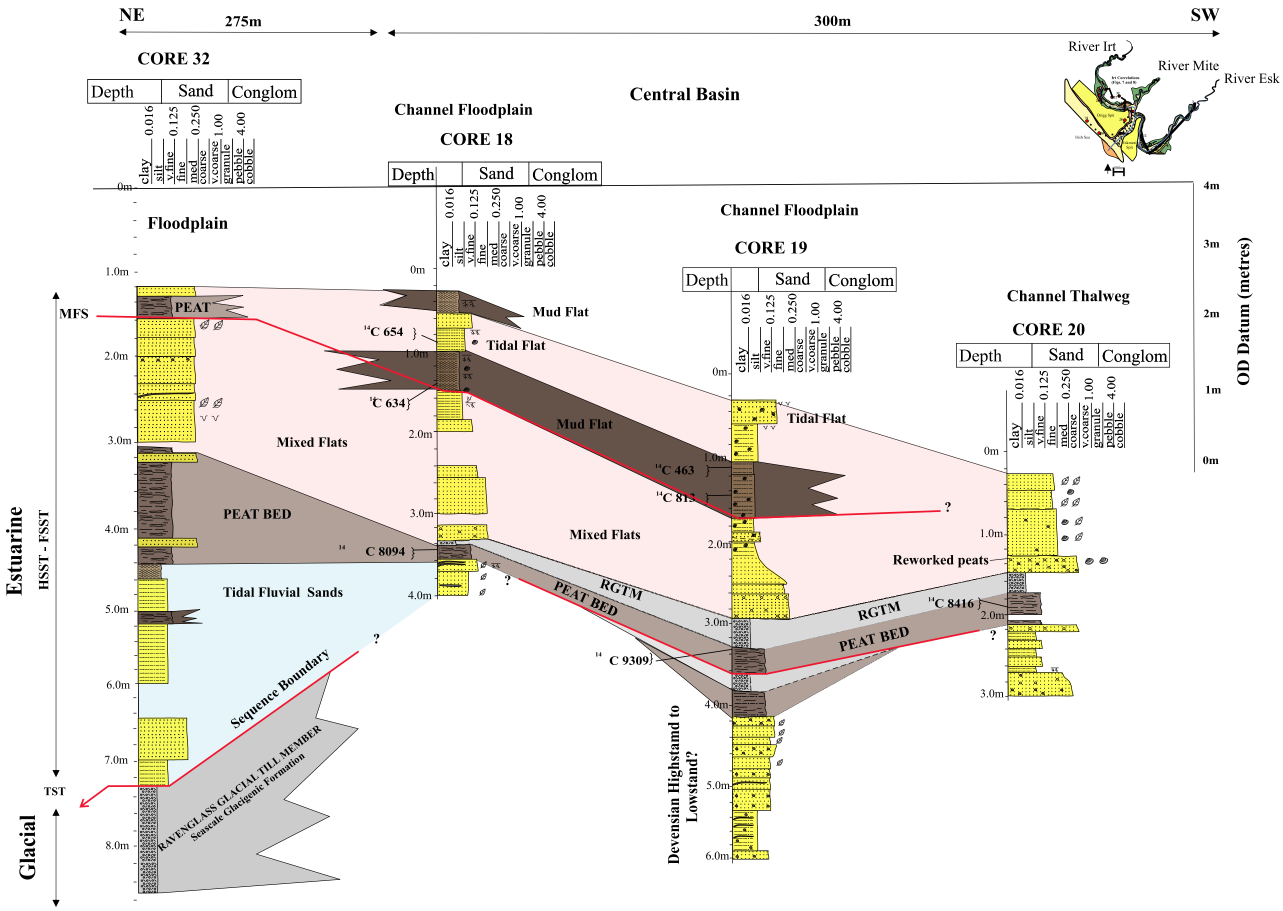


Fig. 8. River Irt correlation panel 2. This panel indicates the River Irt and part of the central basin from the Devensian to present-day with sequence boundaries shown by a red solid line. The RGTM is partially correlatable between cores. The most abundant peat accumulations (^{14}C 9309, 8416 and 8094 BP) and fine-grained sediment occur here, implying that it was a relatively sheltered area above the valley wall throughout most of the lowstand and Holocene transgression – also supported by the back of gravel beds above RGTM.

underlying fluvial–alluvial gravels do not contain organic matter and shells. The peats are between 8094 ± 32 and 9309 ± 38 BP in age and conform to the Holocene transgression (Table 1; Fig. 2).

Considering their variable distribution, location between channels and contact with the fluvial deposits below, the peats represent the first deposits of the valley during the Holocene transgression. The transition from glacial–fluvial deposits below the peats, indicates that some areas of the valley were in isolated and sheltered locations of poorly drained topographical depressions (between palaeo-channels).

Salt and fresh marsh

Salt and fresh marsh sediment is present in cores 1, 3, 7, 8 and 10 (Fig. 6). Commonly distributed throughout the inner estuary and estuary limits, the marsh-related sediment is typically composed of planar laminated, poorly sorted, very fine silts and clays with vegetated tops, in the form of roots. Marsh thickness varies across the estuary from 0.25 to 2.0 m, with the thickest deposits at the proximal channel margins (Fig. 6), where they are continuously correlatable over 3.2 km.

Salt and fresh marsh commonly represent the final stages of the levelling of marine coastal plains, and the presence of marsh above the meanders and sand bars in cores 1, 3, 7, 8 and 10 implies a phase of abandonment as rivers have migrated. Salt and fresh marsh sediment is either linked to transgression or regression; here the stratigraphic context leads to the interpretation that the salt and fresh marsh sediment represents falling sea level (regression).

Table 2. Descriptions of Ravenglass Incised valley-fill facies associations (FA) including: thickness (m), correlation lengths (km) texture and sedimentary structures, location and dominant sedimentary processes, relative sea level and sequence boundaries. RGTM = Ravenglass Glacial Till Member.

Facies	Thickness (m)	Correlation length	Texture and sedimentary structures	Location and processes	Sea level
RGTM	0.15–1.0	Underlies 95% of mapped estuarine stratigraphy	Grey to reddish in colour, very fine-grained (0.063 mm), very poorly sorted clay rich till. Commonly chaotic structure with some shell fragments and small clasts	Inner, central and outer estuary. **Glacial to fluvial processes dominate**	Highstand?
Alluvial Gravels and Coarse Sands	0.6–3.0	Up to 0.5 km	Gravel beds with mixed clasts of sandstone, volcanics and granite up to 7 cm. Commonly shows sharp contact with RGTM	Outer to inner estuary**. Alluvial processes dominate**	Lowstand to transgressive. Base of gravels represents sequence boundary
Estuarine Brown-Black Peats	0.10–1.3	Up to 0.5 km	Black to dark brown in colour, laminated and well-consolidated. Commonly shows sharp contact with RGTM	Inner estuary, central basin and tidal inlet. **Lowland raised bogs – limited fluvial processes**	Transgressive Central basin shielded
Salt and Fresh Marsh	0.25–2.0	Continuous along inner estuarine margins and limits. Up to 3.2 km	Light brown, very fine to fine (0.065–0.125 mm) grained laminated silts, poorly sorted and commonly rooted in top 10 cm. Overall, fining upward grain size trend	Inner estuary, representing the preferential deposition of fine-grained material in an inter-tidal environment. **Estuarine processes dominate**	Highstand to falling
Tidal–Fluvial Channel Sands	0.2–6.5	Up to 2.5 km	Fine (0.25–0.125 mm) to medium (0.25 mm) grained sands, poorly sorted at base with pebbles and moderately to well-sorted upward. Flaser beds, silty laminae and clay drapes common. Proximal settings are finer grained with higher heterogeneity	Inner estuary tidal channel. **Estuarine processes dominate**	Transgressive to highstand
Tidal Sand Bars within Tidal Channels	3.0–5.0	Up to 0.5 km	Orangey brown, fine (0.25–0.125 mm) to medium (0.25–0.35 mm) grained sandstones, moderate to well-sorted with small, disarticulated shell fragments. Sands are commonly massive, structures limited to clay drapes no thicker than 10 cm. Overall sands fine upward	Inner estuary tidal channel. **Estuarine processes dominate**	Highstand

Table 2. (continued)

Facies	Thickness (m)	Correlation length	Texture and sedimentary structures	Location and processes	Sea level
Tidal Meander	1.7–3.5	Up to 1.4 km	Very fine (0.125 mm) to medium (0.25 mm) grained sands and silts. Commonly interbedded, heterogenous and finer in proximal settings. Commonly fines upward	Inner estuary. **Estuarine processes dominate**	Highstand to falling
Tidal Sand Flats	Up to 1.2	Up to 1 km	Fine to medium-grained (0.125–0.25 mm), well-sorted sands, bioturbation near central basin channel	Foreshore and backshore. **Marine processes dominate on foreshore and estuarine on backshore**	Highstand to falling
Aeolian Dunes (Barrier Spits)	Up to 5.5	Drigg and Eskmeal spits occupy a surface area of 3.1 and 2.76 km^2, respectively	Light brown, medium (0.25 mm) to coarse (0.5 mm) grained, moderate to well-sorted sands. Small pebbles present with charcoal fragments	Foreshore and backshore. **Marine wave action and longshore drift forming spit. Wind processes dominate**	HSST–FSST

Sand-dominated sediments

The sand-dominated sediment has been subdivided into a variety of sub-facies from geographic and stratigraphic positions, based on grain size, sorting, sedimentary structures, presence of shell and peat fragments, and presence of minor silt and mud laminae. Five sand-rich facies have been identified for the Ravenglass valley fill: tidal–fluvial deposits, tidal sand bar deposits, tidal meander deposits, outer estuary–shoreface deposits and dune deposits.

Tidal–fluvial channel sands

The tidal–fluvial sand facies (present in all cores except 28; Figs 6, 7, 8 and 9) are present in most cores and throughout the estuary. They represent a landward thinning wedge of sandy estuarine sediment that, in terms of measured thicknesses in core (0.2 to 6.3 m), makes up less than a third of the Holocene valley-fill. The facies are composed of fine−medium (0.125 to 0.25 mm) grained sands with shell debris at the base and higher concentrations of silty-mud laminae in the inner estuary. This sandy facies commonly fines upward, for example in cores 7, 8, 10 and 12. Pebbles and clay drapes are common at the base in the inner estuary sands and reworked peat clasts are common, particularly in the Irt channel and outer estuary. With a radiocarbon age of 7848 ± 40–6827 ± 31 yrs BP, they represent the first estuarine sands within the valley.

The presence of tidally-influenced fluvial sands above the RGTM, suggests that these facies were the first estuarine sand to be deposited within the valley during transgression. Thus, the tidally influenced fluvial sands were deposited as aggrading, transgressive to highstand-facies which onlap the lowstand fluvial deposits during landward migration of the shoreline. The shelly material (dominated by disarticulated bivalves) mixed with the tidal–fluvial sand implies that the sand possibly had a dominant marine source that was reworked by tidal currents, also suggested by Bousher (1999).

Tidal sand bars within tidal channels

The tidal sand bar facies (cores 7, 8, 12, 25 and 26; Figs 6, 8 and 9) are present above the RGTM and peat beds and are deposited along the sinuous section of the Rivers Esk and Irt. Tidal sand bar facies are composed of fine to medium (0.125 to 0.35 mm) grained sands, that are moderately to well-sorted with horizons of small, disarticulated shell debris. The tidal sand bars can be correlated up to 0.5 km in the tidal channels. Pebble beds with shell debris are common at the base and clay drapes are preferentially observed towards the top. Overall, the facies show a significant fining upward profile, at the multi-metre scale, from pebbly gravel, through medium-grained sand capped with laminated silt and mud that is typically vegetated after abandonment.

The deposition of the sand bars symbolizes the time when sea level stabilized, with the development of channel banks. The disarticulated shelly and pebble surfaces most likely reflect internal erosion and migration surfaces within the bar.

Tidal meander (inner estuary)

Tidal meander sediments (cores 1, 3, 10, 18, 19 and 20; Figs 6, 7 and 8), are restricted to the most proximal environments and are composed of planar to slightly inclined lamination, alternating very fine to medium (0.125 to 0.250 mm) grained sand and silt. Flaser bedding occurs in the mid to upper sections of the facies with localized clay drapes. Silt interbeds are common in most proximal settings and they are capped with root-rich fresh marsh. The heterolithic, silt-rich strata are indicative of floodplain development associated with a meandering river system; these facies are restricted to the top 3 m of upper estuary cores because it only developed once sediment had been stabilized by vegetation. The tidal meander sediments can be correlated 1.4 km downstream in the inner estuary.

Tidal sand-flat (outer estuary to upper wave-dominated shoreface)

The outer estuary zones represented by the foreshore, tidal inlet and backshore sediments are medium-grained (0.25 mm), well-sorted sands and show rippled to planar laminations; they are interpreted to represent tidal flats (cores 27, 28, 29, 30 and 31; Fig. 9). This type of sediment is currently present in the foreshore beach and main tidal channel bank sediments and can be correlated up to 1 km over the foreshore. Close to the main tidal channel, the sands form superimposed low-amplitude dunes that are constantly remobilized by tidal currents. Therefore, in the cores, these relatively coarse-grained, rippled to planar laminated sediments are interpreted to result from the progradation of sands at, or on either side of, the mouth of the tidal inlet.

It is noteworthy that there is an absence of well-developed tidal bars in the main tidal channel of the modern Ravenglass Estuary; this is due to the relatively limited modern supply of sand-rich sediment from the rivers and the constant remobilization by tidal currents. The restricted sand-supply and constant remobilization probably lasted throughout the Holocene, and resulted in limited occurrence of tidal bars in the sediment cores. The tidal inlet itself lacks modern accommodation for the development of well-developed bars (Fig. 1B).

Aeolian dunes (barrier spits to outer estuary)

The aeolian deposits (core 28; Fig. 9) are composed of medium to coarse-grained (0.25 to 0.5 mm), moderate to well-sorted sands, with small pebbles and charcoal fragments (*ca* 3 cm) which are common throughout. The aeolian facies only occurs in the top five metres of one core, on the current Drigg Spit; the base of the aeolian deposits occurs after 3910 ± 24 yrs BP (Table 2; Fig. 9). The modern vegetated aeolian dunes, known as the Drigg Spit to the north-west and Eskmeal Spit to the south-east, separate the foreshore and the backshore, here defined as sand-rich shore to the main part of the inner estuary. The dune deposits subsequently constrict the tidal inlet.

DISCUSSION

Controls on facies organization

The controls on facies organization of incised valley-fills are a function of the balance between sea-level rise and sediment supply, coupled with incised valley area and hydrodynamics (Garrison & Bergh, 2006; Davis & Dalrymple, 2010; Virolle *et al.*, 2019, 2020). The dominant controls on the Holocene facies expression and organization of the Ravenglass valley-fill mostly conform to those outlined in the wave to tide-dominated estuarine models by Allen & Posamentier (1993) and Dalrymple *et al.* (1992a). Differences to these idealized models are expected due to local variations in estuarine settings, relative sea level, climate, tectonics and scale. The Ravenglass valley owes its existence to the Devensian lowstand, and its fill to Holocene transgression and highstand. A complete fill through the valley (>9 m) shows that the sequence boundary is characterized by a gravel lag cutting through pre-existing till deposits. In the outer estuary (Fig. 2) the gravels are followed by coarse-grained, cross-bedded sands that generally coarsen upward with some rare heterolithic bedding in the form of clay drapes (Fig. 9, cores 27, 29, 30). In the inner estuary (Fig. 2) the sands fine upward into rhythmic heterolithic bedding and are commonly capped by marsh (Fig. 6, cores 1, 3, 7, 8 and 10) The aeolian dunes are not considered as part of the fill due to their low preservation potential. The evolution of this fill and associated hydrodynamics are discussed below.

Process-based classification of Ravenglass incised valley

The present-day surface of the Ravenglass valley-fill generally shows the typical tripartite zonation of facies with coarse sandy barrier spits/inlet, weakly developed central basin tidal (mud) flats and the common presence of sand bars towards the head of the estuary in the tidal inlet and the Irt and Esk arms systems (Fig. 1); this zonation is normally indicative of wave-dominated systems (Dalrymple *et al.*, 1992a). The central basin of Ravenglass Estuary is weakly developed as it is limited to the extensive mud and mixed tidal flats that have been deposited around the confluence zone of the Rivers Irt and Mite. In terms of timing, these mud and mixed mud flats are fairly recent, dating *ca* 813 ± 20 yrs BP in the River Irt (Fig. 8). The deposition and expansion of the mud and mixed flats is also likely attributed to the development of the turbidity maximum at the point of river confluence, a zone containing higher proportions of suspended sediment (Geyer, 1993; Sanford *et al.*, 2001; Jalón-Rojas *et al.*, 2015). Inhibition of sediment transport via flood currents can also promote extensive central basin muds to form, such as the muds present in the funnel of the Gironde Estuary in south-west France (Allen & Posamentier, 1993; Wells, 1995; Virolle *et al.*, 2019, 2020). However, along the axis of the estuary (Fig. 10), grain size tends to increase seaward and decrease landward, suggesting that, throughout the valley fill, the flood currents promoted fluvial sediment transport rather than inhibited it.

The overall fill of Ravenglass can be categorized as a mixed tide/wave-dominated system since the onset of the Holocene to the present day. Ravenglass Estuary possesses some morphological features like that of wave-dominated estuaries, such as barrier spits and a central basin; however, a strong tidal signature of the facies prevails. The presence of the tidal inlet, tidal sand bars and tidal flats within the system (Figs 1B, 6, 7, 8 and 9) and the lack of a well-developed muddy central basin or bayhead delta, strongly support the interpretation of tide-dominance with wave influence.

During the initial filling of the valley, tidal range was potentially limited compared to the >7 m present-day macro-tidal range, and fluvial and wave action were stronger. The reduced tidal range at the start of estuary filling is supported by the presence of the wave-influenced coarse-grained cross-bedded sands above the sequence boundary in the outer estuary (Fig. 9, cores 27, 28 and 29). In the outer estuary, the sands above the sequence boundary show some evidence of tidal influence suggesting that the tidal channels have always been restricted from wave action (Fig. 6, cores 1, 3 and 10). As the Drigg and Eskmeal spits were migrating to the south-east and north-west, ultimately narrowing the inlet, wave penetration within the valley was likely decreasing and tidal range increasing. This is evident from the transition of the wave-influenced coarse-grained sands to the medium-grained clay draped sands present in cores 27, 29 and 31 at around −3 m OD (Fig. 9) and the development of sand flats above. Based on the coastal processes classification scheme by Ainsworth *et al.* (2011), Ravenglass valley was initiated as a dominantly fluvial system that dissected the coastal plain with the deposition of the gravels (cores 1, 3, 12, 27, 28 and 31; Figs 6, 7 and 9). Landward migration of the shoreline due to rising sea level (Fig. 2) and the formation and migration of the Drigg and Eskmeal barrier spits (Fig. 9, core 28) represents a transition from a fluvial-dominated to wave-dominated system with secondary tide and fluvial influence. Possibly during and after the formation of the barrier spits and tidal inlet, tidal processes became dominant, resulting in extensive estuarine mud flats in the outer estuary (Figs 7 and 8, cores 18, 19, 20, 25 and 26) and sand flats within the inner estuary (Fig. 9, cores 27, 28, 30 and 31).

Throughout the Holocene, valley filling processes have been somewhat segregated, in that wave-dominated processes have controlled deposition in the foreshore and tidal processes have dominated in the tidal inlet and tidal channels. The progradation of the present-day tidal inlet is likely to cut stratigraphically deeper and be less susceptible to later transgressive ravinements. This could lead to wave processes being under-represented in the sedimentary record since the tidal inlet is preferentially preserved. The majority of the valley fill of Ravenglass commenced at the end of the Holocene transgression (Fig. 1B) and tidal ravinement could also have contributed to the

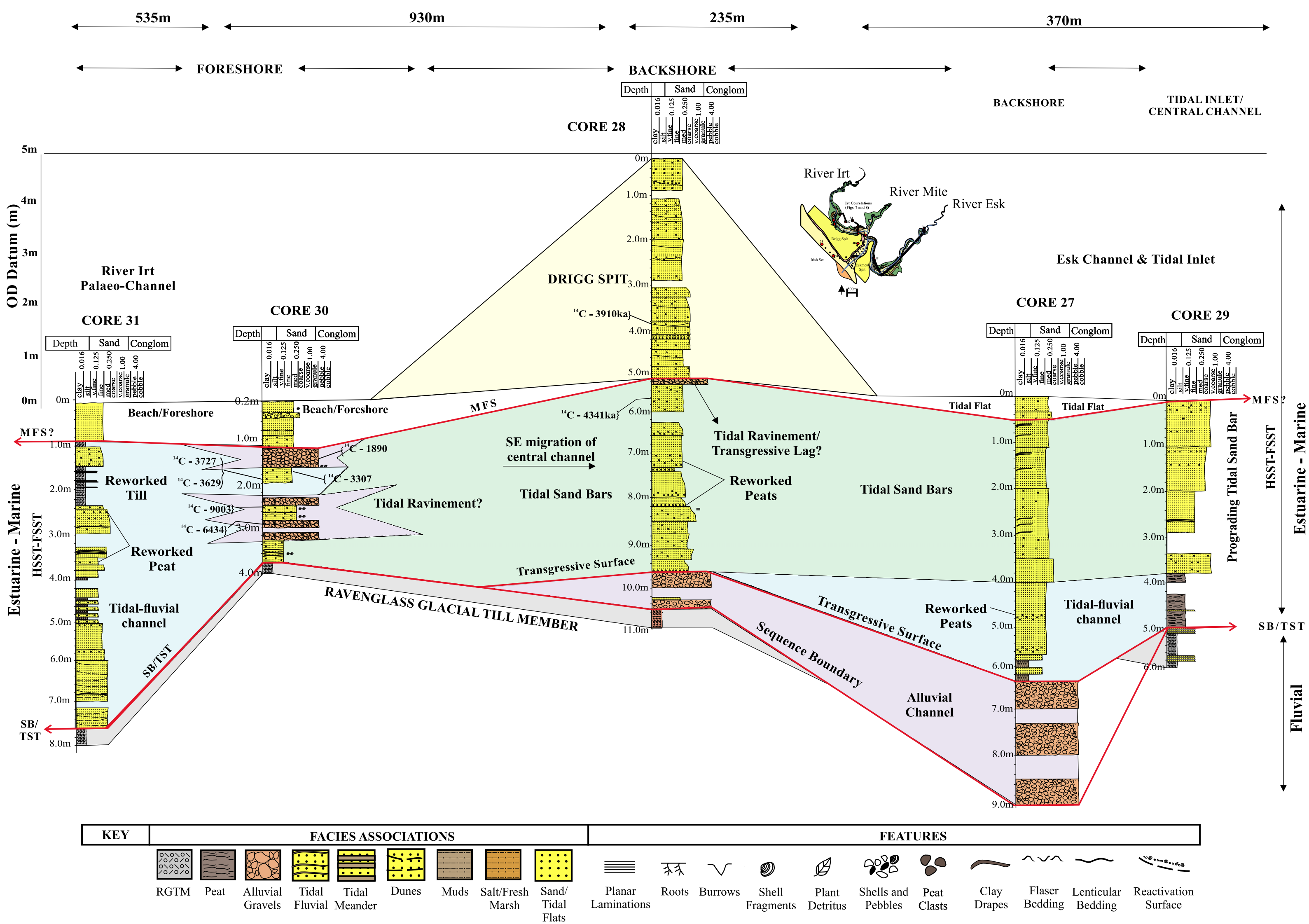


Fig. 9. The foreshore and tidal inlet correlation panel highlighting the outer estuarine facies and sequence stratigraphic surfaces shown by the solid red line. The sequence boundary here becomes amalgamated with the transgressive surface near the valley highs shown by core 30 (potentially a point of tidal ravinement). Core 31 indicates the sequence boundary going deeper into the River Irt palaeo-channel also shown in the first River Irt correlation panel. Reworked peats are also limited to the Irt palaeo-channels. Cores 28 and 29 are in the tidal inlet and show the prograding sand bars. Core 28 shows the evolution of the Drigg Spit.

lack of wave-dominated facies present in the Ravenglass Estuary cores (Fig. 9, cores 27, 28 and 29).

CORRELATION AND ARCHITECTURAL ELEMENTS

The lateral and vertical distribution of the different facies identified from the core logs have here been correlated relative to the RGTM as it occurs throughout most of the inner and outer estuary (Figs 6, 7, 8 and 9). Overall, the architecture of the Ravenglass valley fill, above the sequence boundary, is expressed as a landward thinning wedge of sandy estuarine sediments. Correlation within the Ravenglass estuarine sediment is discussed below and shown in Figs 6, 7, 8 and 9.

Inner estuary to River Esk

The Esk channel shows the most complete section of stratigraphy through the cores. The outer estuarine Esk channel correlation is represented by a set of cores along the channel, from cores 3 and 1 (north-east, most upstream) to 7, 8, 10, 12 and 29 (south-west, most downstream; Fig. 6), covering a distance of 2.5 km. The channel is composed of a distal meandering river system which becomes wider seaward. All the sediment cores are underlain by the correlatable RGTM which is overlain by fluvial gravel beds, with the exception of cores where the fluvial tidal sands directly overlay the RGTM (for example, in cores 7 and 8, Fig. 6). The lack of fluvial gravel beds in cores 7 and 8 suggests that the channel thalweg was not present here during the lowstand incision phase. The gravels are thickest in the most upstream, meandering section of the outer estuary (cores 1 and 3) and generally thin downstream (core 10, Fig. 6). The thick fluvial gravel, that accumulated during lowstand in the proximal floodplain, suggests that the River Esk was wider than it is today and appears to show no time lag between progradation of the shelf during lowstand and upstream fluvial aggradation (Cattaneo & Steel, 2003). Fluvial gravel in core 1, drilled in the modern-day floodplain, is 25 cm thick while in core 3, only 185 m away, the fluvial gravel is 3 m thick (Fig. 6). The difference in the thickness of the fluvial gravel from the two cores from the tidal meander (cores 1 and 3; Figs 1 and 6) emphasizes the heterogeneity that can occur over short distances.

Tidal sand bars, up to 5 m thick, have accumulated in the straighter parts of the Esk channel and have good internal correlation over 500 m (cores 7 and 8, Fig. 6). However, sand bar facies cannot be correlated with cores 1.8 km upstream (cores 1 and 3).

Salt and fresh marsh now occurs and can be correlated in all cores in the upper Esk channel (cores 1, 3, 7, 8 and 10; Fig. 6) along the channel banks and caps abandoned channels and vegetated bars.

The River Irt and central basin

The River Irt is shown by two north-west – south-east correlation panels, the first highlights cores 22, 23, 25 and 26 (Figs 7 and 8) over 1.45 km. The RGTM is only penetrated in core 25 on panel 1 (Fig. 7) and is immediately overlain by a tidal sand bar (cores 25 and 26; Fig. 1) that fines upward to mud. The sands show reworked peat clasts implying erosion of pre-existing peat beds nearby. There are thick mud beds at the base of cores 22 and 23 which are overlain by tidal fluvial sands with rare clay drapes and flaser bedding. Tidal sand-flats, mixed-flats and mud-flats developed through time indicating the abandonment and reactivation of the River Irt palaeo-channel. The cores of the River Irt and central basin also show no gravel above the limited RGTM indicating that this was possibly a location near the top of the valley walls or interfluves. It is possible that the RGTM and gravels exist deeper in the palaeovalley of the River Irt (Fig. 2) but the boreholes never penetrated the thalweg of the palaeovalley. Lack of peat beds and shell fragments limited the potential for dating of these cores.

The second correlation panel of the Irt River arm covers a distance of 0.6 km and (Fig. 8) is shown by cores 18, 19 and 20, located in the active channel, and core 32, located in the floodplain (Fig. 1B). The underlying RGTM and the transgressive peat beds are overlain by tidal fluvial sands. The lack of gravel beds here suggests that the channel thalweg did not incise this location during sea-level fall. As the tidal–fluvial sands were the first estuarine sediment deposits above the peat and till and the coarsest of all sediment in these cores, most likely reflect the migration of the River Irt and ultimately the confluence of all three rivers. The ^{14}C date in the peat in core 18 is 8094 ± 32 yrs BP, which implies that the migration occurred after this.

However, the subsequent sedimentation in the form of mixed-flats and mud-flats is much younger (*ca* 634 ± 26 yrs BP). The sequence of dates suggests that the recent formation of muddy estuarine deposits (*ca* 634 ± 26 yrs BP) was limited to mud and silt grade material, which is possibly a result of barrier spit formation and dampening of wave action that promoted the recent development of a newly developed central basin at the river confluence. The recent development of tidal flats in the central basin may also have been encouraged by the confluence of the three rivers. The correlation panels (Figs 7 and 8, cores 18, 19, 20, 25 and 26) show that, through the past *ca* 9000 yrs BP, the central basin was located on a topographical high, near the valley wall, old palaeo-channels of the floodplain (cores 32, 22 and 23) are also present. The current channel shows the general sandy thalweg sands and off-channel mixed-flats to mud-flats through the surface deposition (Fig. 8, cores 18, 19 and 20).

Outer estuary to foreshore, backshore and tidal inlet

The foreshore, backshore and tidal inlet are underlain by the RGTM and the gravel beds are limited to core 27 and core 28 (Fig. 9) which are interpreted to represent the River Esk palaeo-channel. The gravel beds are thought to be of fluvial origin as they are of a similar thickness to the gravel beds in the inner estuary meandering channel belt (Fig. 6, cores 1 and 3). Fluvial gravel beds are absent in cores 29, 30 and 31 for different reasons. Core 29 shows a sharp transition from the RGTM to peats, indicating that this was a sheltered depression along the Esk valley during sea-level rise. The RGTM in core 31 is immediately overlain by marine sands, potentially implying that a major Irt palaeo-channel existed here during the lowstand phase feeding a sand bar in core 31. This interpretation is supported by the mapped palaeo-river Irt in Fig. 4. The RGTM was deposited almost 4 m lower in core 31 compared to core 30, supporting the interpretation of a palaeo-channel in core 31 and a possible wave ravinement surface in core 30. The limited deposition of sand, and the presence of repeat gravel above the sand in core 30, may imply that this was an area of continued shoreface erosion during shoreline retreat. Wave action may have promoted a landward migration of gravels at this location. The presence of the peat bed and absence of gravels in core 29 above the RGTM (Fig. 9) also reveals that no major channel existed here until the Esk channel migrated as a result of the formation of the barrier spits. Core 30 shows very little in the way of correlation with core 31 over a distance of 0.5 km, and their sediment bodies are quite different in both volume and character. The absence of the thicker tidal sand bodies in core 30 suggests that this could have been a wave ravinement surface that progressively moved landward during shoreface retreat. The ravinement surface may have reworked previous deposits and surfaces such as the transgressive systems tract, therefore the wave ravinement surface may also become amalgamated with the sequence boundary. Evidence in the form of reworked peat clasts (Figs 7, 8 and 9) also suggests extensive reworking of peat beds during this time as channels migrated.

Summary of lateral and vertical connectivity

Connectivity within the Ravenglass incised valley sediments is best in the channels that have remained relatively stable during the Holocene transgression. The River Esk panel (Fig. 6) indicates that the initial fluvial–tidal channel sands can be correlated over 2.5 km from the inner to the outer estuary and range in thickness from 1 to 3 m. Tidally influenced sand bars within the channels can be correlated over 0.5 km and range from 3 to 5 m in thickness (Fig. 6, cores 7 and 8), showing similar sediment character but varying thicknesses. 1.8 km upstream of the sand bars, correlation of the fluvial–tidal sands becomes difficult due to the extensive meandering of the tidal channels upstream. The increased heterogeneity upstream is common to all three rivers that feed the system.

Peat beds are extensive and thickest in the River Irt floodplain (Fig. 8), ranging from 1.2 m thick in core 32 to 0.2 m downstream in cores 18, 19 and 20 (Fig. 8). Not all of the peat beds can be correlated. The tidally-influenced fluvial sands, ranging from 0.8 to 1.5 m in thickness, may be correlated up to 1.4 km between cores 22, 23, 25 and 32 (Figs 7 and 8). The tidally influenced fluvial sands thin towards the active Irt channel to 1.5 m (Figs 7 and 8) and are not present in cores 18, 19 and 20, located in the active floodplain. A tidally influenced sand bar ranging from 1.6 to 2.6 m can be correlated *ca* 0.2 km along the River Irt (Fig. 7, cores 25 and 26) thinning downstream into tidal flats (Fig. 8, cores 18, 19 and 20). The sand bar is capped with 1.3 m of muds that also thin to 0.5 m downstream towards the channel floodplain (Figs 7 and 8, cores 22, 23, 18 and 19). The lack of gravels and limited deposition of the RGTM within the cores suggests that the channel thalweg was never penetrated making correlation more difficult.

In the outer estuary, the thickest (6 m) tidal–fluvial sands are represented by the palaeo-Irt in core 31 and show little correlation with core 30, located 0.5 km to the south-east (Fig. 9). The sand bars within the tidal inlet show excellent correlation both laterally and vertically. The tidal sand bars range in thickness from 3.5 to 4.4 m and can be correlated over lengths of *ca* 1.5 km.

SYNTHESIS OF VALLEY CREATION AND FILL

A synthesis of the Ravenglass valley creation, classification and fill throughout the Holocene to present is demonstrated in Fig. 10 and is summarized below.

According to existing estuary classification schemes (Dalrymple *et al.*, 1992a; Davis & Dalrymple, 2010; Boyd *et al.*, 2011), the Ravenglass incised valley-fill is categorized as a small, macro-tidal, mixed wave to tide-dominated system that initially resulted from coastal plain incision and subsequent transgression. The incision cut through pre-existing glacial stratigraphy (Busby & Merritt, 1999). The creation of the Ravenglass incised valley occurred during the Late Devensian Period (17 000 to 12 000 yrs BP), attributed to changes in relative sea level linked to glacio-isostacy (Figs 2 and 8A). When the maximum period of sea-level fall was reached between *ca* 12 000–10 500 yrs BP, the present-day coastline was exposed and incised by the Rivers Irt, Esk and Mite (Fig. 8A). According to modelled sea-level curves for the Ravenglass area, the period of incision lasted for 6500 yrs, between *ca* 18 000 and 11 500 yrs BP (Lloyd *et al.*, 2013). During this initial phase of valley development, the proto-Drigg and Eskmeal sand spits must have been developing, suggesting a dominant role for wave activity over tidal or fluvial action. Despite the differences in the scale of estuaries, the duration of the Ravenglass incision period is broadly similar to those reported for the Holocene Gironde incised valley, which had an incision period of 8000 yrs (Allen & Posamentier, 1993) and the Holocene Qiantang River estuary, which had an incision period of *ca* 5000 yrs BP (Zhang *et al.*, 2014).

The presence of basal gravel beds (Figs 6 and 9) implies that the Early Holocene palaeo-Rivers Esk and Irt had a higher energy than the present-day rivers and a bedload that was capable of cutting through the shelf and forming the Ravenglass valley complex. The post-glacial vegetation may have also favoured rivers carrying gravels and glacial outwash (Kasse *et al.*, 2005). A straighter profile for the palaeo-Rivers Esk, Irt and Mite has been previously proposed by the Halcrow Group (2013). The Irt followed a roughly straight trajectory until at least 410 yrs BP, as evidenced by a historical map by John Speed, published in the year 1610 (Speed, 1610). By 1794, the River Irt had deviated from the south-west to north-east, following the present-day shoreline and merged with the River Mite (Cary, 1794). At present, there is no published historical map evidence for when the Esk deviated to the north but the absence of fluvial gravels in core 12 (Fig. 6) proves that the deviation happened long after the main Holocene incision phase. The peat bed towards the base of core 12 implies that no fluvial deposition occurred in this sheltered location and that the River Esk did not migrate into the central basin until after the transgressive peat had been deposited.

The deeper parts of cores 18, 19, 20 and 32 (Fig. 8) are dominated by peat with negligible sandy sediment. This suggests that the palaeo-River Irt feeding this area, the present-day central basin, had low flow volume and minimal bedload. The absence of fluvial gravel, repetition of peat beds and the young stratigraphic age of the sediment in the central basin (>813 ± 20 yrs BP, cores 18, 19 and 20) can be used to infer that the River Irt, with its greater flow volume and presumably greater bed load, did not deviate its course to the south and merge with the diminutive River Mite 226 yrs ago.

There seems to be no evidence in the map of the depth to glacial till (Fig. 4) for an initial straight path for the Early Holocene palaeo-River Esk. The northward migration of the southern Eskmeals spit was probably responsible for the northward deviation of the larger River Esk and its subsequent merger with the smaller River Mite. The capture of the River Esk by the River Mite presumably contributed to the accumulation of the tidal–fluvial sands and the prograding tidal sands and muds in the upper parts of cores 18, 19 and 20 (Fig. 8).

STRATIGRAPHIC SURFACES OF RAVENGLASS INCISED VALLEY

The stratigraphic organization and relative stratigraphic surfaces within the Ravenglass incised valley fill are shown in Fig. 10 and discussed below.

Sequence boundary and lowstand systems tracts – gravels (LST)

The marine lowstand (12 000 to 10 500 yrs BP) of the Late Devensian into the early Holocene (Fig. 2) is categorized as a time when isostatic rebound outstripped sea-level rise (Merritt & Auton, 2000; Lloyd *et al.*, 2013; Figs 10 and 11A). In the Ravenglass valley, this stratigraphic surface is expressed by the fluvial–alluvial gravels and coarse sands, the base of which marks the sequence boundary with the RGTM. The fluvial gravels and sands have a high preservation potential due to the subsequent rapid onlapping of the transgressive estuarine sediments. During lowstand, sediment was bypassed through the valley and was most likely deposited seaward (west) of the present-day coastline. The rapid lowstand and transgression that the Ravenglass Valley underwent, prior to and into the Holocene, limited the amount of time possible for fluvial aggradation. The gravel beds are thicker in the outer than in the inner estuary (Figs 6 to 9) because the palaeo-valleys, on the glacial till surface (Fig. 4), were steeper than the present-day valleys. This resulted in high energy palaeo-rivers capable of carrying gravel further downstream.

Transgressive systems tract – peat and estuarine tidal–fluvial sands (TST)

During transgression, after the deposition of the till and gravel, the incised valley was inundated (Figs 10 and 11B). This resulted in an accumulation of peat beds in sheltered areas between the main channels, and estuarine tidal–fluvial sands within the tidal channels. The base of the transgressive surface separates the lower fluvial gravels and coarse sands with estuarine peats, sands and muds (Figs 6 to 9). In the inner estuarine zone, the surface is well-defined particularly along the palaeo-river Esk, however, in contrast, in the River Irt, central basin and outer estuarine zones, the transgressive surface becomes amalgamated with the sequence boundary along the palaeo-valley walls. Contrary to other Holocene estuaries, that typically show large-scale transgressive deposits (Martinsen, 1994; Hori *et al.*, 2001; Wilson *et al.*, 2007; Chaumillon *et al.*, 2010b), the Ravenglass Estuary demonstrates that most of the backfill began at the end of transgression when maximum accommodation was achieved. Deposition continued into, and throughout, the highstand and falling stage systems tract. The limited accumulation of transgressive deposits within the Ravenglass valley-fill are most likely a result of the rapid transgression and coastal flooding, during which the rate of sea-level rise outpaced sediment supply. The rapid transgression limited the thickness of the aggrading, onlapping sediment within the valley during the landward migration of the coastline, evident in the Esk channel profile (Fig. 6).

Highstand systems tract (HSST) – tidal bar channel sands, tidal meanders, central basin muds and prograding tidal sand bars

Post-glacial sea level within the Ravenglass coastal area is estimated to have reached its peak of +2 m OD around 6000 yrs BP (Lloyd *et al.*, 2013) and has fallen since (Figs 10 and 11C to E). At this peak stage of sea-level rise, accommodation within the valley achieved its maximum point (Figs 10, 11C and 11D). Consequently, infilling of the system mostly occurred during this time, and into, the sea-level regression (Figs 10, 11D and 11E). After 6000 yrs BP, the falling sea level formed a seaward-prograding, tide-dominated system consisting of meandering point bars with alternate sand bars, sand-flats, mud-flats, gravels and a small, restricted, muddy central basin with a prograding tidal inlet.

Due to the nature of progradation during the highstand-into-regression, the top of the highstand surface is downlapping onto the transgressive estuarine wedge (Figs 6 and 9). During this time of infilling, the upper estuary tidal limit migrated downstream, promoting fluvial gravel to gradually work its way downstream. This is prominent on the banks of the present day Esk Channel.

Reservoir implications

Ravenglass Estuary is a good analogue for assessing simple tide-dominated incised valley-fill models in terms of stratigraphic organization with the opportunity to analyse a single fill (corresponding to a single sea-level cycle). Although the present day Ravenglass Estuary appears to be mud-rich, the cores (Figs 6 to 9) show that majority of the infill is very much sand-dominated. The presence of sand above the

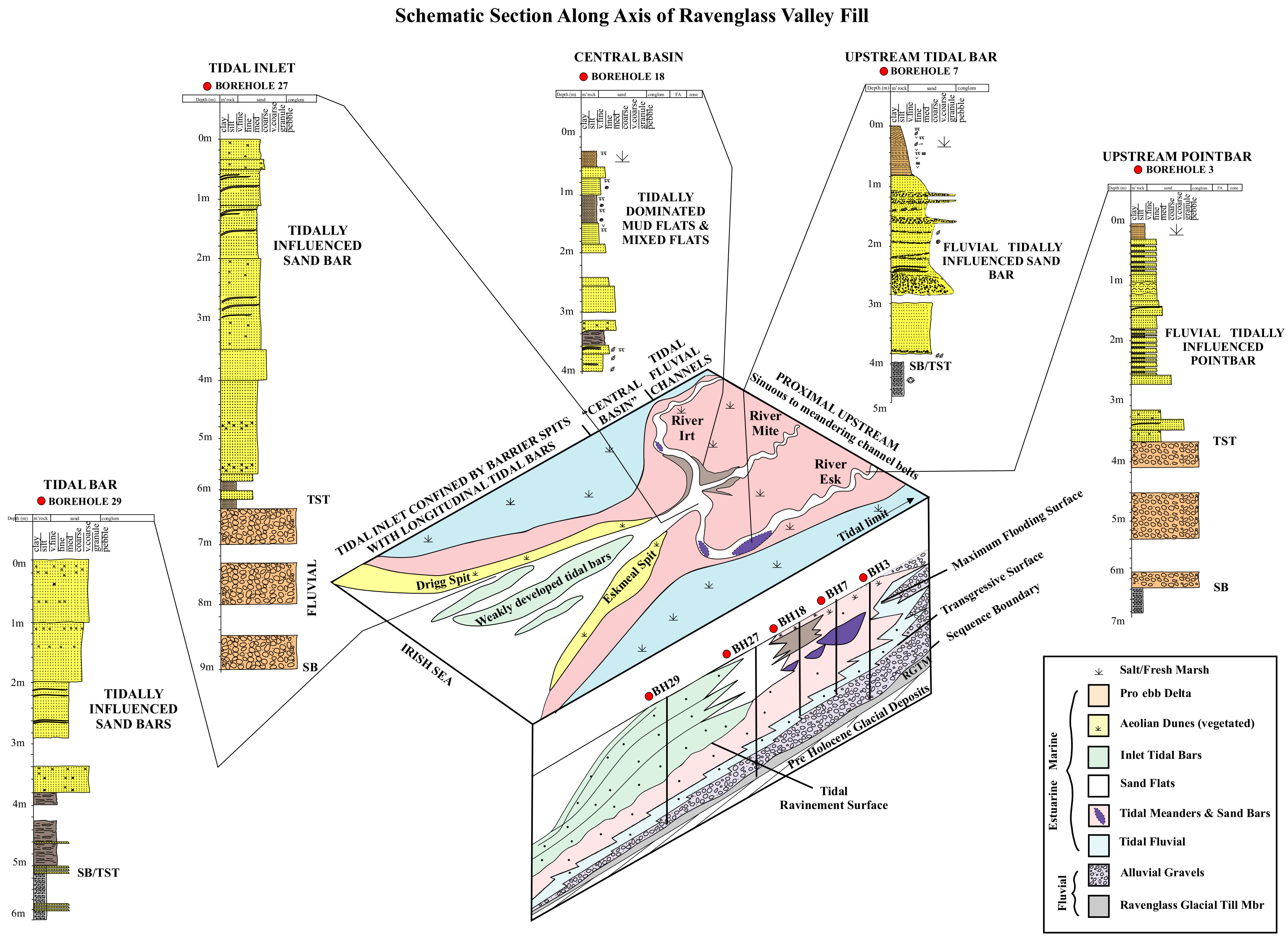


Fig. 10. Schematic stratigraphic section along the axis of the Ravenglass incised valley fill with representative cores and facies distributions. The facies distributions are a result of an initial lowstand represented by the fluvial gravels, marking the sequence boundary. The valley underwent rapid landward migration of the shoreline and deposition was limited to the tidal fluvial channel sands. During highstand the system started prograding and most of the filling occurred in the form of tidal meanders, tidal sand bars, mudflats and mixed flats. Along the axis of the estuary, grain size tends to increase seaward (core 29) and decrease landward (cores 1 and 3).

sequence boundary implies that the majority of the coarse-grained sand filling the tidal channels and inlet is of marine origin. As previously mentioned, this is supported by the presence of shelly detritus hosted in medium to coarse-grained sands. Tidal processes have been dominant since the onset of transgression as double clay drapes are recorded in the first sand deposits after the sequence boundary in core 8 (Fig. 6) along the Esk channel. This study is a rare modern analogue of a sandy, tide-dominated estuary. Discussed below is the significance of the Ravenglass sedimentary system for building models of sand/mud ratios, grain size and sand body connectivity in subsurface reservoirs.

Sand/mud ratio and grain size

Based on the evidence from 19 Holocene sediment cores, the Ravenglass Estuary-fill is dominated by sand. It should be noted that this interpretation is based on the 19 cores acquired; however parts of the subsurface remain unsampled. Although, the localized sand/mud ratio varies from upstream to downstream, sandy deposits typically represent 75% of all cores, the remainder being peat (5%), gravel (10%) and mud (10%; Figs 6 to 9). The upstream meandering portions of the tidal channel system contain greater proportions of interbedded finer grained sand and mud compared to the cleaner, coarser grained sands in the downstream, sinuous portions of the channels (Figs 5 to 7). The downstream coarser sands lack well-developed mud beds and have accumulated as thick, continuous sands with rare mud drapes (Figs 6 and 9).

The most abundant mud deposition occurred along the River Irt and within the central basin (Figs 7 and 8), which was a result of the backfilling of the River Irt valley and migration to the south-east to merge with the Rivers Mite and Esk. The confluence of all three rivers (Fig. 11D and E) allowed for the recent development of the classical tripartite zonation of facies (Dalrymple *et al.*, 1992b; Boyd *et al.*, 2011); inner estuarine medium–coarse-grained sandy tidal channels, mud-rich central basin and marine influenced sands at the estuary mouth.

The sand/mud ratio is highest within the marine-influenced tidal inlet and foreshore (Fig. 9). The tidal inlet hosts large incipient tidal bars (Fig. 11E) with limited mud quantities (Fig. 9) due to the remobilization of bar sediment by the ebb and flood tides. The sand/mud ratio in foreshore sediments is similar to the modern tidal inlet and lacks mud deposition. This lack of mud in the foreshore and tidal inlet can be attributed to the high energy shoreline processes remobilizing the sediment and lack of slack water within the tidal inlet.

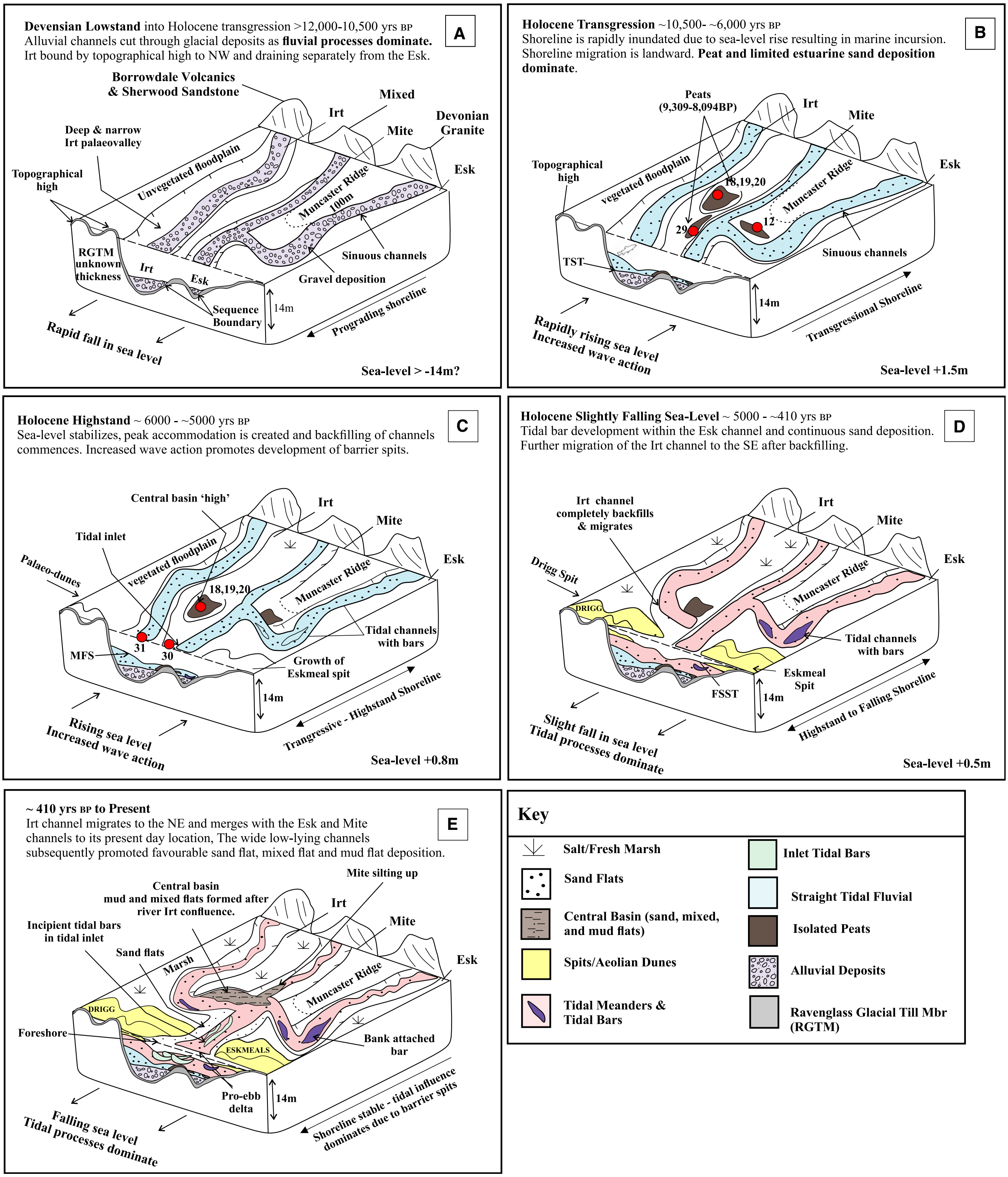
Connectivity

By analogy to the subsurface, the connectivity of sand is heterogenous across the estuarine system but, as the estuary is sand-dominated, most of the sediment looks as if it has good connectivity. The Esk arm of the estuary represents a good reservoir in terms of connectivity (Fig. 6). Tidal fluvial sands and tidally-influenced sand bars (cores 7, 8, 10, 12 and 29) are well-connected up to 5.2 km through the river course. The tidal sand bars show varying thickness across the estuary between 4 m and 6 m. The Esk system becomes less sandy upstream, promoting reservoir compartmentalization due to the presence of extensive mud and interfluves (cores 1 and 3). Even under the Saltcoats mudflats, the River Irt cores 32, 18, 19 and 20 (Figs 1B and 7) have thin (30 to 150 cm) correlatable, sand-dominated deposits which become coarser grained towards the thalweg over 1.5 km. The outer Esk, typifying outer estuarine deposits, represents excellent connectivity (cores 27, 28 and 29; Figs 6 and 9) of sandy sediments ranging from 4 to 6 m. The connectivity of palaeo-Esk and Mite sands is excellent due to the interpretation that the flow path has been stable for about 10 000 yrs (Fig. 11A to E).

In contrast to the Esk–Mite system, the palaeo-Irt looks as if it has limited sand connectivity with the palaeo-Esk, as shown by tidal-ravinement deposits in core 30 (Fig. 9) and the palaeotopography map which reveals a high between the River Irt and Esk on the present-day foreshore and in the central basin (Fig. 4). The connectivity of palaeo-Irt and palaeo-Esk–Mite sands is limited due to the recent (between 410 to 226 yrs BP) merging of the Irt with the Esk–Mite channels (Fig. 11D and E). These observations indicate that channel migration can happen in a short time period (*ca* 10 ka), resulting in complicated reservoir architecture.

SYNTHESIS

This study of the Ravenglass incised valley, post-glacial fill provides a practical means of highlighting the facies distributions and stratigraphic differences of glacio-induced estuaries of macro-tidal, tide-dominated settings. This paper has revealed the characteristics of the



estuary that have developed in the palaeo-Ravenglass incised valley during the last transgression. This has been achieved using 19 cores drilled into the Holocene estuarine sediment, and sediment facies analysis, sediment distribution and high-resolution ^{14}C ages.

It is proposed here that Ravenglass valley formed and subsequently filled in five identifiable stages:

1 The Devensian glacial lowstand, when isostatic rebound outstripped sea-level rise,

Fig. 11. Morphological evolution and corresponding facies of Ravenglass Incised Valley since of onset and throughout the Holocene transgression. (A) Incision on the newly exposed post-glacial shelf during the Devensian lowstand (12 000 yrs BP) by a series of sinuous rivers depositing gravel and coarse sands. (B) Holocene transgression which began around 10 500 BP and continued to around 6000 BP. The initial flooding and landward migration of the shelf promoted peat bed deposition in sheltered areas between the sandy tidal channels. (C) The Holocene Highstand (6000 to 50 000 yrs BP) was a time of sea-level stabilization when peak accommodation is reached and backfilling of the valleys occurs. The palaeo-Drigg Spit began migrating to the south-east. (D) Sea level begins to fall from 5000 yrs BP to around 410 yrs BP and the migration of the Drigg Spit and backfilling of the River Irt forced migration to the south-east. Tidal sand bars and meandering channel belts accumulated in the River Esk. (E) The River Irt migrates to the north-east and joins the Rivers Mite and Esk. The now backfilled, wide and shallow channels have promoted favourable estuarine conditions resulting in the development of the muddy central basin.

between 12 000 and 10 500 yrs BP (Fig. 2). This promoted shelf incision represented by the fluvial–alluvial gravel overlying the RGTM (Figs 10 and 11A). Fluvial processes were dominant and net sediment was bypassed to the lowstand shelf. During this time there was a basinward shift in facies (Figs 2, 10 and 11A).

2 The Early Holocene rapid transgression, which was characterized by a phase of relative sea-level rise, occurring between *ca* 10 500 and 6000 yrs BP (Fig. 2). During this time, net sediment transport was landward with transgressive sediments onlapping alluvial gravels or the Ravenglass Glacial Till Member (RGTM) where the gravels were not present (Figs 10 and 11B). This resulted in estuarine deposition, with peats initially forming on locally isolated highs, between channels, and the transitional fluvial–estuarine sands subsequently filling the deepest part of the valleys. During this time, it is here suggested that much of the sand supplied to the estuary was of marine origin due to the presence of shelly debris. Sea level rapidly outpaced sediment supply, limiting the amount of time for the transgressive estuarine deposits to form. The transgressive deposits are therefore relatively thin. As the first transgressive deposits are sandy, it implies that a reasonable amount of sand was available on the shelf to be reworked into the valley by tidal currents.

3 The Holocene highstand, which occurred as sea level stabilized, and accommodation reached its maximum point at around 6000 to 5000 yrs BP (Figs 10 and 11C). Back-filling of the Irt and Esk valleys continued at this time. The stabilizing of sea level and dominant wave-action may have promoted the growth of the palaeo-Drigg and Eskmeals Spits. Despite increased wave action, tidal signatures were still prevalent in the estuarine sediment since the onset of deposition. The spits demonstrate that wave-dominated elements can play an important role in the evolution of tide-dominated systems.

4 A minor fall in relative sea level from 5000 yrs BP to the present day, resulting in the estuarine system filling and prograding (Figs 10 and 11D). In-channel tidal bars started to build in the downstream tidal channels, upstream meanders prograded and the system stepped seaward. Radiocarbon dating suggests that most of the fill occurred during the highstand to falling stage systems tract, highlighting that not all estuarine sedimentation corresponds to the transgressive phase.

5 Complete backfill of the Irt and Esk channels is the final stage (*ca* 410 to 226 yrs BP, Fig. 11E). This was possibly coincident with the southward migration of the Drigg spit which closed off the mouth of the River Irt which thus forced the merging of the Irt with the Rivers Mite and Esk to adopt the present-day morphology.

These stages of evolution within the Ravenglass incised valley system have resulted in a particular facies organization not widely discussed in the literature. The stratigraphic relationships and facies models (Figs 6 to 9) enable the construction of a detailed depositional model of the Ravenglass incised valley-fill.

The results of this study can be used to interpret the development of several other, mixed energy macrotidal estuaries in the stratigraphic rock record, that may also correspond to late transgressive – highstand conditions. It may also be used to predict reservoir architecture, lateral and vertical connectivity and sand quality within such a system.

The work presented here can be used to predict connectivity and sand-quality within incised valley-fill sediments. The Esk–Mite system has very good connectivity and sand quality, largely due to the stability of the flow path of the rivers. The Irt, in contrast, is poorly connected to the Esk–Mite system because of the relatively recent southward deflection of the flow path and consequent merging of the rivers. Sand–mud ratios decrease upstream in both the Irt and Esk estuarine fills. The coarsest and cleanest sands are found in the tidal inlet and on the foreshore.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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