

Distribution, geomorphology and lithofacies of cliff-top storm deposits: Examples from the high-energy coasts of Scotland and Ireland

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Abstract

Cliff-top storm deposits (CTSDs) occur on cliffs at elevations of up to 50 m above sea level at exposed sites on the deep-water coasts of the British Isles. This study examines the distribution, geomorphology and lithofacies of CTSDs at sites from Shetland, Orkney, Caithness and the Outer Hebrides in Scotland and from the Aran Islands in Galway Bay in Ireland. CTSDs are generated largely by the quarrying of blocks from the cliff top, and transported by green water bores across cliff-top platforms and ramps to be deposited in backing ridges or as debris spreads. Maximum boulder sizes reach 48 m³ but it is likely that much larger blocks can be quarried, prior to disintegration during transport. Eye-witness accounts and field mapping demonstrate that formation and modification of CTSDs has continued during major storms over recent decades. Recent CTSDs bury a range of man-made debris but older deposits lack this and instead show weathering effects that indicate a longer residence time. In Shetland OSL dates on intercalated sands suggest that the oldest CTSDs date from ~ 800 AD. Radiocarbon dates on shell buried inside CTSD ridges relate to major storms between 1700 and 1900. CTSDs represent an overlooked archive of storm sedimentation that has great potential for the elucidation of local storm chronologies. CTSDs also provide evidence of wave impacts on any part of the cliff face or top, in fundamental contrast to the concentration of wave action at the cliff foot implicit in traditional models of the erosion of rock coasts. © 2006 Elsevier B.V. All rights reserved.

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1. Introduction

A striking feature of several sites on the rock coasts of the British Isles that are exposed to Atlantic and North Sea storm waves is the presence of wave-generated

accumulations of large boulders on the tops of cliffs at up to 50 m OD (Figs. 1 and 2) (Steers, 1973; Hall, 1996; Hansom, 2001; May and Hansom, 2003; Williams and Hall, 2004). The quarrying and transport of large blocks of rock by waves at elevations well above sea level has long been recognised (Hibbert-Ware, 1822; Stevenson, 1845; Peach, 1864; Geikie, 1887) but has received little recent scientific attention. The boulder accumulations on west Shetland have been referred to as storm beaches

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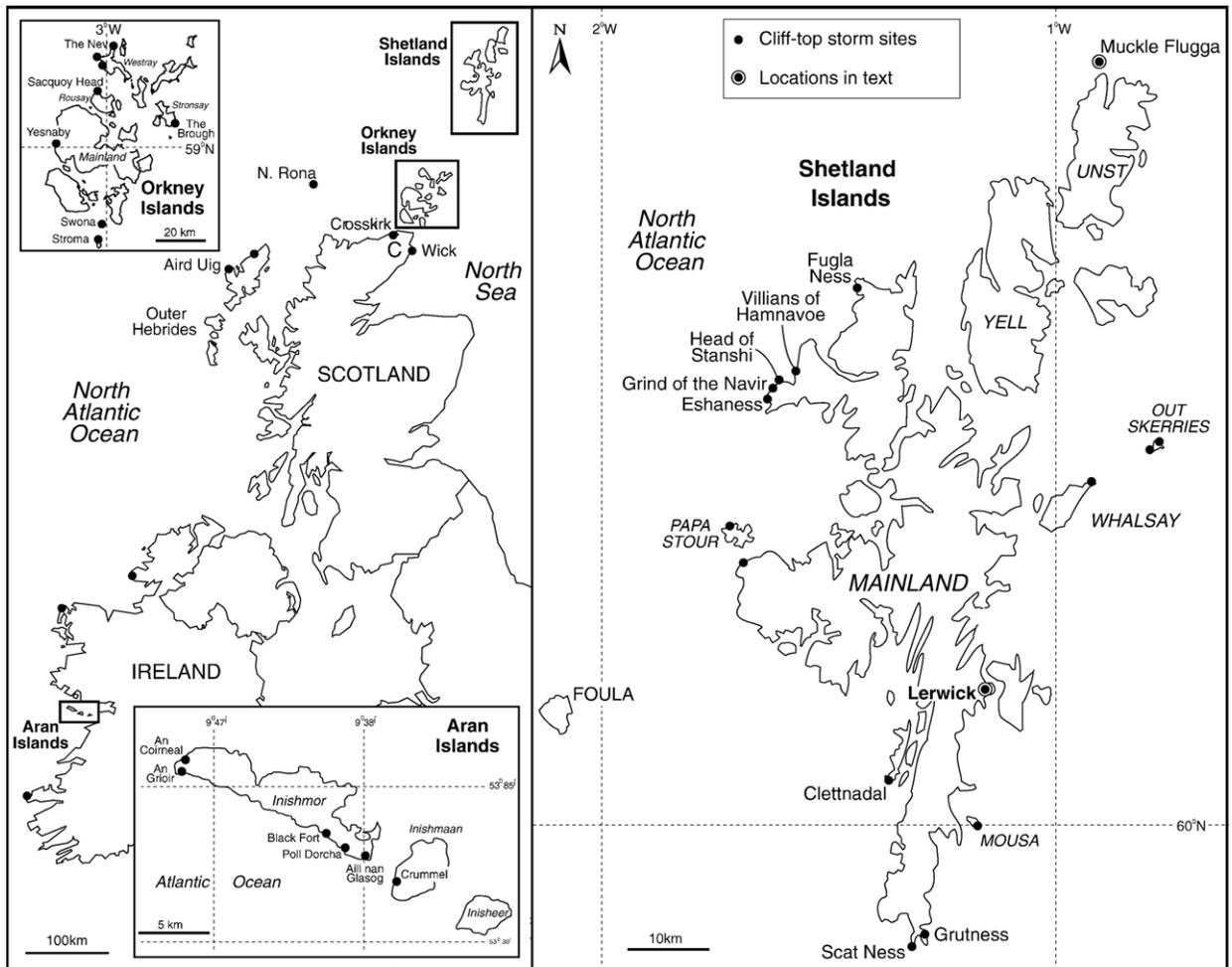


Fig. 1. Location map. C Caithness.

(Mykura, 1976) and on Aran as block beaches (Kinehan et al., 1871), a recognition of shared characteristics with storm-generated boulder ridges found close to modern sea level, notably in the localised development of substantial steep-faced ridges composed of seaward-dipping, imbricate boulders. However, the exceptional height above sea level of the cliff-top storm deposits (CTSDs) reported here, together with the angularity, lack of sorting and large size of the boulders (many are well over 1 m in length) are not features commonly associated with modern storm beaches. A range of evidence for historic and recent block detachment and records of transport during storms has allowed recognition of the role of extreme storm waves in generating these cliff-top boulder deposits (Hall, 1996; Hansom, 2001; Williams and Hall, 2004).

The study sites have direct bearing on continuing debates over the role of tsunami or storm waves in the formation of boulder accumulations on cliffs at elevations

well above present sea level in many parts of the world (Bourrouilh-Le Jan and Talandier, 1985; Bryant et al., 1992; Hearty, 1997; Noormets et al., 2002). Although, there are few documented effects of major tsunami on the coasts of the British Isles over the last 1000 years (Bondevik et al., 2005), the sites examined here often have direct observations of the effects of wave overtopping of cliffs in recent storms. The CTSDs also widely incorporate man-made debris, including plastic fishing floats and other items, and several boulder accumulations have been remobilised in recent years as is reported below. It is important to note that many of the CTSD sites reported here are backed by flat-topped or landward-dipping surfaces and so cannot be the result of toppling or rockfall from above. Neither are they the result of emergence, since all of the coasts described in detail below have a history of relative sea level rise over the Holocene. These CTSD sites in Scotland and Ireland are



Fig. 2. Esha Ness, Mainland, Shetland in 1973. Vertical cliffs in Devonian andesitic tuffs, 30–35 m high. Scattered storm boulders (arrowed) rest on cliff-top ramp. The lighthouse is at 50 m OD. IPR/68-47C British Geological Survey. © NERC. All rights reserved.

important in demonstrating the recent and continuing ability of mid-latitude storm waves in the generation, transport and deposition of large blocks at elevations up to 40 m above sea level (Williams and Hall, 2004).

Understanding the origins of CTSDs is important also for other reasons. The evolution of cliffs is poorly understood, partly because the timescales for change are long (Trenhaile, 2002), yet CTSDs are products of episodes of rapid cliff erosion during storms along some of the most exposed hard rock coasts in the North Atlantic (Williams, 2004). Traditional models of cliff evolution focus on the action of breaking waves at the cliff base but CTSDs relate to erosion by storm waves on the upper cliff, a hitherto neglected process zone. Plunging cliffs fronted by deep water may receive extreme waves largely unmodified from the deep ocean. Maximum recorded wave heights in the North Atlantic reach 29 m (Holliday et al., 2006). Under suitable near-shore configurations, high wave energy may be transferred through impacts of extreme waves to rocks high on, or even beyond, the cliff face (Hansom, 2001). The deposits left on the cliff top thus represent an archive of the impacts of storm waves over timescales of 10^1 – 10^3 yr at locations where instrumented wave records are available only for recent decades. Elsewhere, the characteristics of boulder accumulations at altitude on rock cliffs have allowed the modelling of wave height, power and behaviour (Nott, 1997; Noormets et al., 2002; Felton, 2002; Nott, 2003). The cliff-top storm deposits described

here share many of the characteristics of deposits reported in other high-energy wave environments associated with tropical cyclones and mid-latitude depression systems (Nott, 2004). CTSDs therefore have the potential to provide wide-ranging insights into the effects of extreme waves impacting on hard rock cliffs.

This paper describes in detail for the first time the distribution, geomorphological setting and lithofacies of CTSDs across multiple sites in Scotland and Ireland. Evidence is presented for the age and origin of these intriguing deposits. Linked papers will examine in detail the processes of CTSD formation at The Grind of the Navir, Shetland, via a) modelling using both field and laboratory data (Hansom et al., *in press*) and b) establishing the rates and patterns of erosion during recent centuries on this exposed headland (Hall et al., *in press*).

2. Methods

The distribution and characteristics of the CTSDs reported here have been established by field mapping since 1992. Major storms affected Shetland in 1992 and 1993 and the effects of these storms at CTSD sites were mapped in 1995 (Table 1). These GPS surveys provided geomorphological maps of Out Skerries and Villians of Hamnavoe (Fig. 3). The key site of The Grind of the Navir (The Grind) has been surveyed by GPS at 1:100 and also monitored at intervals between 1995 and 2005 to establish recent changes (Hall et al., *in press*).

Table 1
Characteristics of the cliff-top storm deposits on Shetland

	Location	Site	NGR	1992 and 1993 storms							Earlier storms		
				A	B	C	D	E	F	G	H	I	J
North Atlantic	North Roe	Fugla Ness	HU 313914	W/NW	6	8	9		0.9	0.6	12	1.4	0.9
	Villians of Hamnavoe	South Head	HU 238824	W	20	26	40	51	1.8	1.2	42	2.1	1.4
		VH1	HU 239815	W	5	14	15	20	1.2	0.7	15	2.8	1.2
		VH2	HU 239819	W	8	16	15	14	1.5	0.8	14	3.9	1.2
	Eshaness	VH3	HU 240813	W		6	7	11	1.5	1.0	11	2.2	1.3
		Head of Stanshi	HU 214805	W	20	20	20	20	1.3	1.05	20	1.5	1.1
		Grind of the Navir	HU 213804	W	15–19	17	19	19	1.8	1.1	19	2.1	1.2
	Papa Stour	Lighthouse	HU 205785	W/SW	32	34	42	51	1.6	1.0	40	1.9	1.1
		Virda Field	HU 149625	W/NW	20	30	32		0.6	0.4	36	1.05	0.6
	Burra	Clettnadal	HU 356302	NW	19	15	19	21	0.4	0.25	19	0.5	0.3
	Scat Ness	Ness of Burgi	HU 386083	W	9	11	11		1	0.4	17	3.1	1.1
		Grutness	HU 409103	SE		7	8		0.7	0.4	9	2	1.0
	North Sea	Out Skerries	Nackie Geo	HU 694724	NE	11	17	17	25	1.5	1.0	21	1.9
South Ward			HU 683712	S	20	10	20	32	1	0.5	20	1.5	0.7
Mioness			HU 666706	SE	16	18	23	30	0.9	0.4	24	1.4	0.6
Mousa		Green Head	HU 463232	SE	8	18	19		1.1	0.7	19	1.4	0.8

CTSD sites on Shetland.

A Direction of dominant storm waves.

B Height (m OD) of cliff or ramp (R).

1992/1993 Storms.

C Maximum elevation (m OD) of boulders moved by waves.

D Maximum elevation (m OD) of wave wash.

E Maximum elevation (m OD) of air-throw debris.

F *A* axis length (m) of largest block moved.

G Mean *B* axis lengths (m) of 5 largest blocks moved.

Earlier storms.

H Maximum elevation (m OD) of boulders moved by waves.

I *A* axis length (m) of largest block moved.

J Mean *B* axis lengths (m) of 5 largest blocks moved.

NGR UK National Grid Reference.

Cliff profiles were surveyed using a compass and clinometer. Large boulders and boulder clusters were located by hand-held GPS and photographed, in part to allow future changes in boulder distribution to be identified. *A*-axis orientation of elongate boulders and imbricate boulder clusters was measured to establish directions of wave approach and allow comparison with directions of prevailing wind-driven storm waves. At Villians of Hamnavoe, Shetland, surveys along three transects in May 1992 recorded the presence of bedrock clasts resting on green turf to establish the distribution of air-throw debris from the storm of 1/1/1992.

The distribution of spray-tolerant lichen on boulders and platforms was also mapped. Detailed mapping at The Grind allowed comparison with photographs (sourced from Lerwick Museum) covering the period from 1900 to 2005, indicate that the black lichen *V. maura* will cover >50% of a rock surface in 70 years. The bright orange *Caloplaca marina* and grey *Leconara* sp. are established more quickly, with large colonies developed

on gravestones made of local bedrock in coastal churchyards in Aran and Shetland in 20–30 years and 50–100% cover in 100 years (Williams and Hall, 2004; Hall et al., in press). Comminuted shell was sampled from two locations in the interior of the main CTSD ridge at The Grind for radiocarbon dating. Sand samples were taken from the rear of the cliff-top gravel and sand sheet at Villians of Hamnavoe for OSL dating (Sommerville et al., 2003).

3. Distribution of CTSDs

Boulder accumulations occur on cliff tops at numerous sites exposed to storm waves along the North Atlantic and North Sea coasts of Scotland (Fig. 1). On Shetland, CTSDs are restricted in their development to the outer coast (Flinn, 1964) at sites where cliffs are exposed to the south-west to north-west on the Atlantic coast and to the south and south-east on the North Sea coast (Figs. 1 and 3) (Hall, 1993; Hansom, 2001). Where

cliff tops lie above 25 m OD, boulder accumulations are rare, as wave action generally does not reach to these elevations. Striking exceptions, where scoured cliff tops and boulder accumulations exist at up to 40 m OD, occur in Devonian tuffs and ignimbrites at South Head, Villians of Hamnavoe (Fig. 3B), Esha Ness (Fig. 2) (Mykura and Phemister, 1976), and rhyolites at Virda Field, Papa Stour, (Table 1). Most CTSDs occur between 10 and 25 m OD but rarely extend more than 2 km along the coastline.

CTSDs also occur in the Devonian flagstones on the Atlantic coast of Orkney at 10–20 m OD (Steers, 1973; Hall, 1996) and at The Brough on Stronsay (Berry, 2000) on the North Sea coast (Fig. 1). The northern end of Stroma is reported to have been inundated by storm waves in 1862, leaving wreckage on cliff tops at >20 m OD (CW Peach in Geikie, 1887). In Caithness, CTSDs are recorded only from flagstone sites near Wick (Crampton and Carruthers, 1914) and at Crosskirk Bay (Woodman-Smith, 2004).

In the Outer Hebrides, CTSDs are well developed on the remote island of North Rona (Fig. 1) where its northern promontory of Fianuis lies fully exposed to Atlantic waves. Accumulations of angular boulders of Lewisian gneiss form a substantial 500 m long boulder ridge at an average height of 2 m OD and which sits at the rear of a broad rock platform at 15 m OD that is regularly swept bare of debris by storm waves, (Steers, 1973). At Aird Uig in Harris, scouring by waves has stripped vegetation, soil and regolith from a 600 m length of the cliff top to expose a Lewisian gneiss bedrock surface at a height of 20–30 m OD.

CTSDs also occur at widely-spaced sites on the west coast of Ireland (Fig. 1). On Aran, boulder accumulations extend along several kilometres of strike-aligned cliff top in Carboniferous limestone on the south-western coast of the islands. The CTSD accumulations reach 31 m OD on Inish Mór and extend up to 50 m OD on Inishmaan (Kinehan et al., 1871; Williams and Hall, 2004).

3.1. Controls on CTSD deposits

Although the extensive rock coasts of Shetland, Orkney and Caithness show numerous places where cliff tops have been stripped of vegetation, soil and regolith by storm waves (c.f. Bird, 1993), only a few sites appear to provide the combination of exposure, bathymetry, cliff form and cliff-top ramp height that permits the accumulation of CTSDs. Bathymetry appears to be a fundamental control on the distribution of CTSDs and the presence of wide shore platforms and low rock islands close to sea level (skerries) generally precludes the formation of cliff-top deposits, probably

on account of enhanced wave attenuation over these surfaces. Shetland appears to be particularly suitable for CTSD formation due to plunging cliffs and the virtual absence of shore platform development (Flinn, 1964; May and Hansom, 2003). Immediately adjacent to CTSDs localities in Shetland, water depths generally reach 50 m within 500 m of the cliff base. Similarly, at CTSD sites on the Atlantic coast of Orkney, intertidal rock platforms are either absent or very narrow. Water depths reach 30 m within 500 m of the shore at Sacquoy Head, The Nev and Yesnaby. Water depths are more modest off Aran, from 3–18 m, where the sea floor slope reflects the seaward dip of the Carboniferous Limestone.

3.2. Geomorphic features

Shorelines with CTSDs commonly show a sequence of zones of varying width. Moving away from the shoreline, these comprise the cliff, the storm wave scour zone, the boulder accumulation zone and a landward zone characterised by wave-splash and air-throw debris (Fig. 4A). Each zone carries an assemblage of features that can be matched between sites to provide a model of CTSD characteristics (Fig. 4B).

3.2.1. Cliff profiles

Although profiles vary considerably between sites (Fig. 5), the most common configuration is a near-vertical cliff extending below low water mark, topped by a flat rock platform or gently-sloping ramp. In the volcanic rocks of Eshaness, Shetland, the cliff-top ramp falls gently inland following the dip of the Devonian lavas, tuffs and ignimbrites (Mykura and Phemister, 1976)(Fig. 5A). A similar rectilinear geometry occurs in Orkney where vertical cliffs are topped by a horizontal or gently-inclined ramp conforming to the dip of the Devonian flags and sandstones (Fig. 5B). The stepped cliff profiles in the Aran Islands also reflect a strong structural influence (Fig. 5C). The regional dip of the Carboniferous Limestone is 3–5° towards the SSW, facing the dominant wave approach direction (Williams and Hall, 2004). In Aran, wave exploitation of occasional thin shale horizons has led to undercutting and eventual collapse of cliff faces, creating extensive, gently inclined terraces at the foot of steep cliff sections. Mega-blocks derived from cliff collapse rest locally on these terraces. However the main boulder accumulations generally occur towards the rear of higher ramp-like terraces above cliffs of 5–20 m high. In Shetland, stepped cliffs developed in Devonian volcanic rocks also show wave scour to heights of 40 m at South Head, Villians of Hamnavoe (Fig. 6A). Other cliffs with

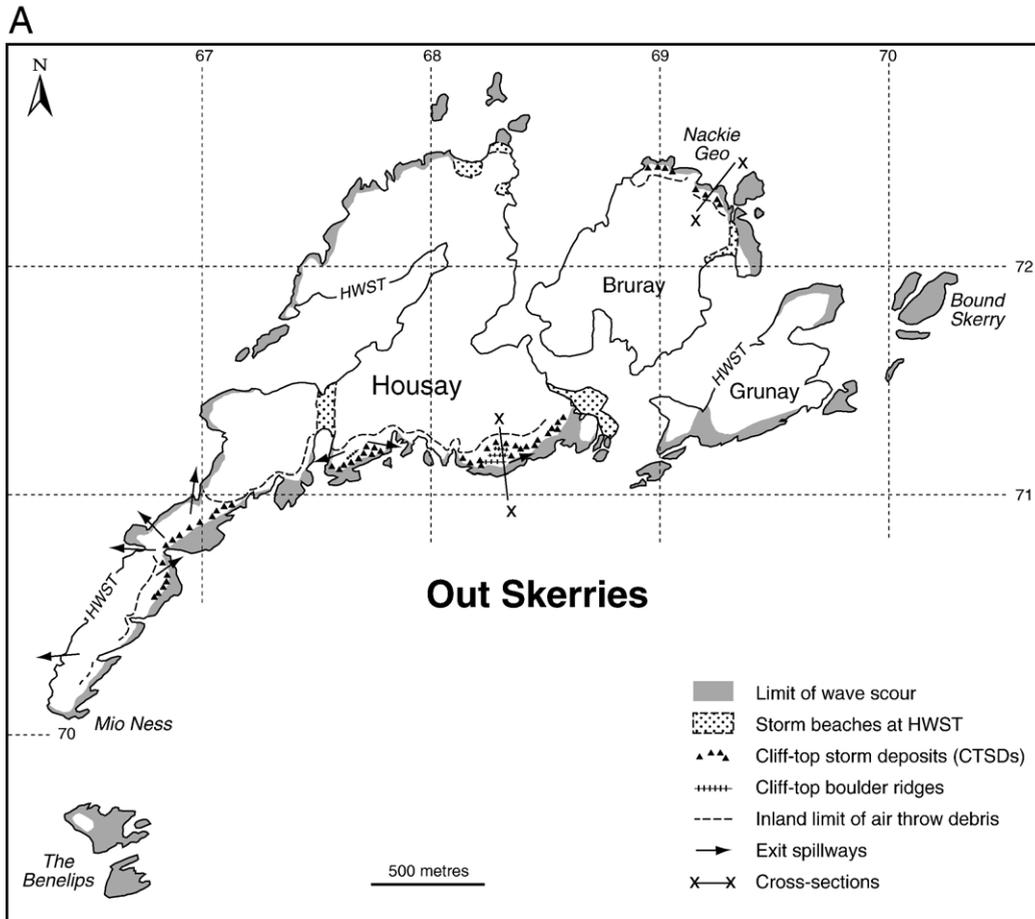


Fig. 3. Geomorphological maps of the Shetland coast. A. Out Skerries. B. Villians of Hamnavoe.

CTSDs show a ramped profile, notably at Crosskirk, Wick (Fig. 5B) and at Inishmaan, with gradients of up to 10° .

3.2.2. Cliff-top rock platforms or ramps

Boulder accumulations usually occur back from the cliff edge, behind rock surfaces that are largely swept clear of debris by storm wave activity. In Shetland the most extensive wave-scoured rock surfaces are the platforms, 40–150 m wide, at Villians of Hamnavoe (Mactaggart, 1999), where, at one site, the platform is backed by a sheet of pebbles, granular gravel and coarse shelly sand at 16–18 m OD (Fig. 3B). At Head of Stanshi and the adjoining headland of The Grind, the platform is scoured during major storms by waves that overtop cliffs that are 15–18 m high. Staircase geos may act here to focus wave activity. At The Grind, for example, the cliff-top platform is 40–60 m wide and indented by a shallow pond that fills a stepped bedrock cavity developed by

block quarrying by waves (Fig. 5A). Further south still, the cliffs at Esha Ness show some of the highest wave-scoured surfaces in Shetland, at up to 40 m OD. Here, above vertical cliffs, CTSDs occur at the rear of cliff-top ramps inclined at 12° to seaward (Fig. 2).

In Orkney, the cliff-top ramp at The Nev, Westray dips gently inland at an elevation of 12–15 m (Fig. 5B). At Yesnaby, the cliff top has an upper ramp section inclined at 6° to seaward and the weathered Devonian flagstones are also being actively stripped from the rear of the ramp where gulleys have been incised by draining wave water. At Sacquoy Head, Rousay, the cliff at Quoy Geo is mainly vertical above a stepped base and the cliff-top shows a 40 m wide wave-washed platform, sloping seaward at 3° . Nearby at the Kilns of Brin Novan (HY 382349), a sequence of blowholes penetrate the cliff-top platform, with the youngest of the blowholes eroding into and postdating the CTSDs that occur at its rear (Hall, 1996).

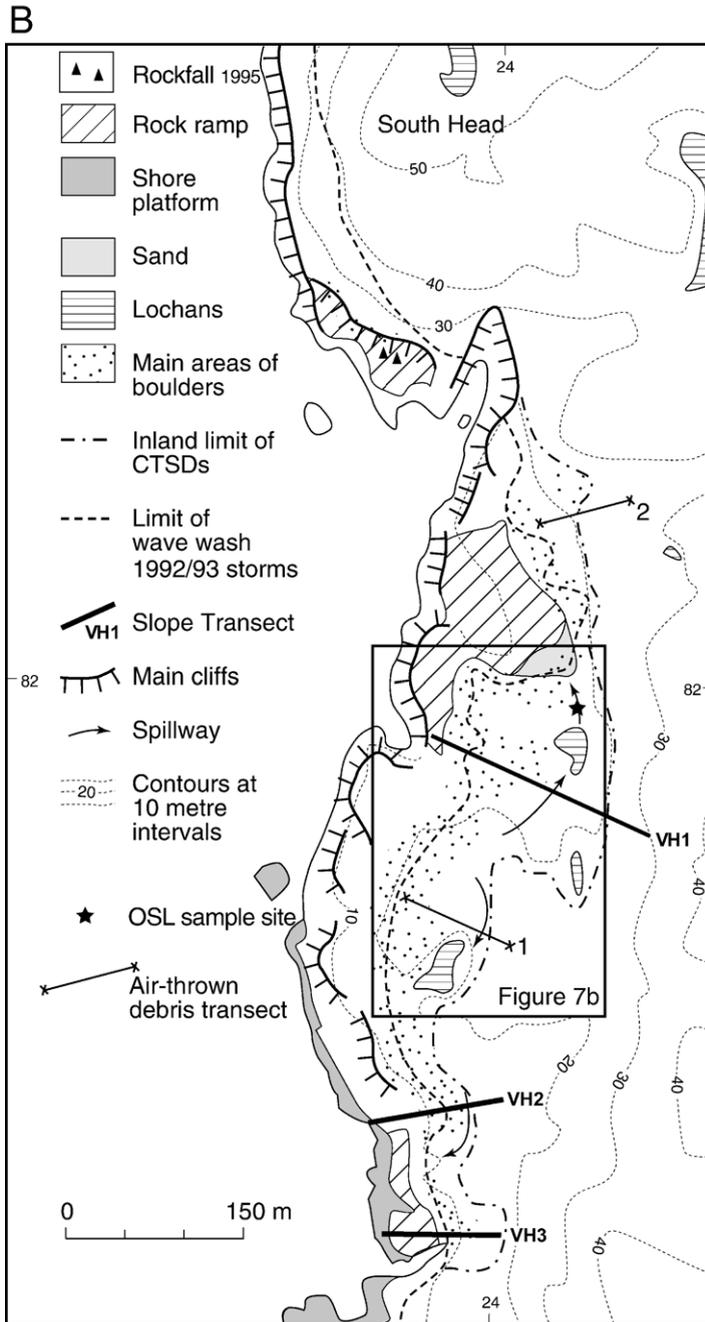


Fig. 3 (continued).

In Ireland, the Aran CTSDs show significant differences in geomorphic features compared with Orkney and Shetland. The cliff-top platforms are narrower, generally around 20 m in width, and usually backed by a single boulder ridge 1–6 m high and 3–35 m wide (Fig. 6B). The boulder ridge may pass inland into boulder spreads but these generally extend only 10–

20 m behind the crest of the ridge (Williams and Hall, 2004). The cliff-top zone subject to current and historic wave activity is therefore considerably narrower than in Orkney and Shetland.

A common feature of these scoured zones is the presence of fresh scars and sockets where recent clast removal has occurred. The scars and sockets show

unweathered surfaces that retain sharp edges and are free of the algae and lichen cover found on adjacent surfaces. Sockets are most common at the cliff edge or on the seaward side of small rock steps that occur on the cliff-top platform or ramp. Edges are clearly preferred sites for quarrying of blocks by waves. Where multiple blocks have been sourced from a single site during one or more storms, a quarry zone is evident, with sockets and joint surfaces showing progressive discoloration and lichen growth according to the time interval since the quarrying of individual blocks. For example, the platform at The Grind shows multiple sockets, with fresh joint-bounded surfaces from which boulders of ignimbrite up to 0.64 m^3 were removed by wave activity in storms in the early 1990s and on January 12th 2005 (Fig. 7). In the storms of 1992 and 1993, quarry zones at Villians of Hamnavoe released larger blocks, up to 1.8 m^3 (Table 1). However, the largest boulders at these two sites reach 1.0 and 8.9 m^3 respectively and relate to earlier and perhaps more severe storms. On Aran, the largest blocks reach 40 m^3 (Fig. 8). In many locations, fresh boulders can be traced to sockets of equivalent dimensions and geometry on the cliff-edge or cliff-top platform. Transport from the socket to the place of rest at the rear of the platform typically involves carry distances of 10–50 m.

At Poll Dorcha, Inish Mór, there are indications that blocks up to 20 m *A*-axis length have been quarried and lifted recently by waves and then moved unbroken, prior to cracking on reaching the base of the storm ridge. The dimensions of a fresh socket on the cliff edge of 290 m^3 can be matched to the cumulative dimensions of a group of blocks 32 m inland, of which the largest block is now 18 m^3 . The example suggests that the size of blocks in CTSDs gives only a minimum estimate of the size of the bedrock block that is initially lifted because jointed or large tabular blocks tend to fracture and break up during wave transport.

Isolated clusters of lichen-covered, large boulders may also occur on the rock ramp (Fig. 8). In Inish Mór, these boulders reach 48 m^3 and boulder clusters retain coarse clastic matrix material. In Shetland, the lichen-covered clusters of blocks up to 6 m^3 on the ramp at Villians of Hamnavoe lack matrix material but must relate to major storms before the 1990s as the blocks were not overturned in the major storms of 1/1/1992 and 17/1/1993. However, smaller boulders at the Villians of Hamnavoe were overturned during these storms and now sit with lichen-covered surfaces facing downwards.

In some places, cliff-top platforms and isolated boulder clusters are covered with algae and lichen. Grass is also found growing within joints on the platform

(Fig. 6B). Such platforms lack superficial boulder spreads but, nevertheless, also possess a backing boulder ridge covered by extensive lichen growth. It seems likely that such areas of platform and ridges have become relatively inactive in recent years, a change perhaps related to the changing geometry of the fronting cliff.

Particularly where a boulder ridge is absent or poorly developed at the rear of the cliff-top platform or ramp, it is common to find a low eroded terrace edge of vegetation-covered regolith. Usually only a few metres high, the terrace marks the landward edge of the cliff-top platform. This stripped zone is subject to wave wash during major storms and, more generally, to the effects of splash and spray. On closely-jointed rock surfaces, the rear of the platform is especially susceptible to active weathering by salt and frost. On the coast of Shetland and Orkney, the stripped zone is present along much longer stretches of cliff-line than those which carry CTSDs. Its maximum elevation declines from headlands to bays and it provides a valuable indicator of the maximum limit of wave run-up on cliffs during major storms (Figs. 3 and 4A). Similar stripped zones have been noted on cliffs on high energy coasts in Australia (Baker, 1958).

3.2.3. Boulder accumulation zones

A striking feature of CTSDs is the accumulation of boulders as individual clasts, clusters, spreads and ridges. Wave-transported boulders may extend inland of the limits of modern storm wave wash onto vegetated cliff-top surfaces. The most landward CTSDs may in time become buried by vegetation or peat growth.

Locally, the cliff-top boulder accumulations form ridges parallel to the coast. The rear of the platform may carry clusters and piles of boulders deposited following recent transport across the platform or from wave erosion of the base of the boulder ridge. On an unusually straight section of coast at South Ward, Out Skerries, a sequence of three parallel storm ridges is sited on a 10 m OD platform some 60 m landward of a 20 m high cliff (Figs. 3A and 5A). A particularly fine sequence of three boulder ridges, up to 3.5 m high and with ignimbrite boulders up to 2.5 m *A*-axis, occurs at 15–18 m OD at The Grind of the Navir (Fig. 9). The ridges rest on a platform some 50–60 m landward of the cliff edge. In Aran, water issuing from a large, steep-sided blowhole at Aill na nGlasog, Inish Mór, has quarried boulders from an area of limestone platform and deposited them in a set of three arcuate storm ridges. A sequence of three ridges also occurs at Crummel on Inishmaan.

Where ridges are well-developed, the landward ridge represents the inland limit of wave action. As with storm boulder ridges close to current sea level, the CTSDs may

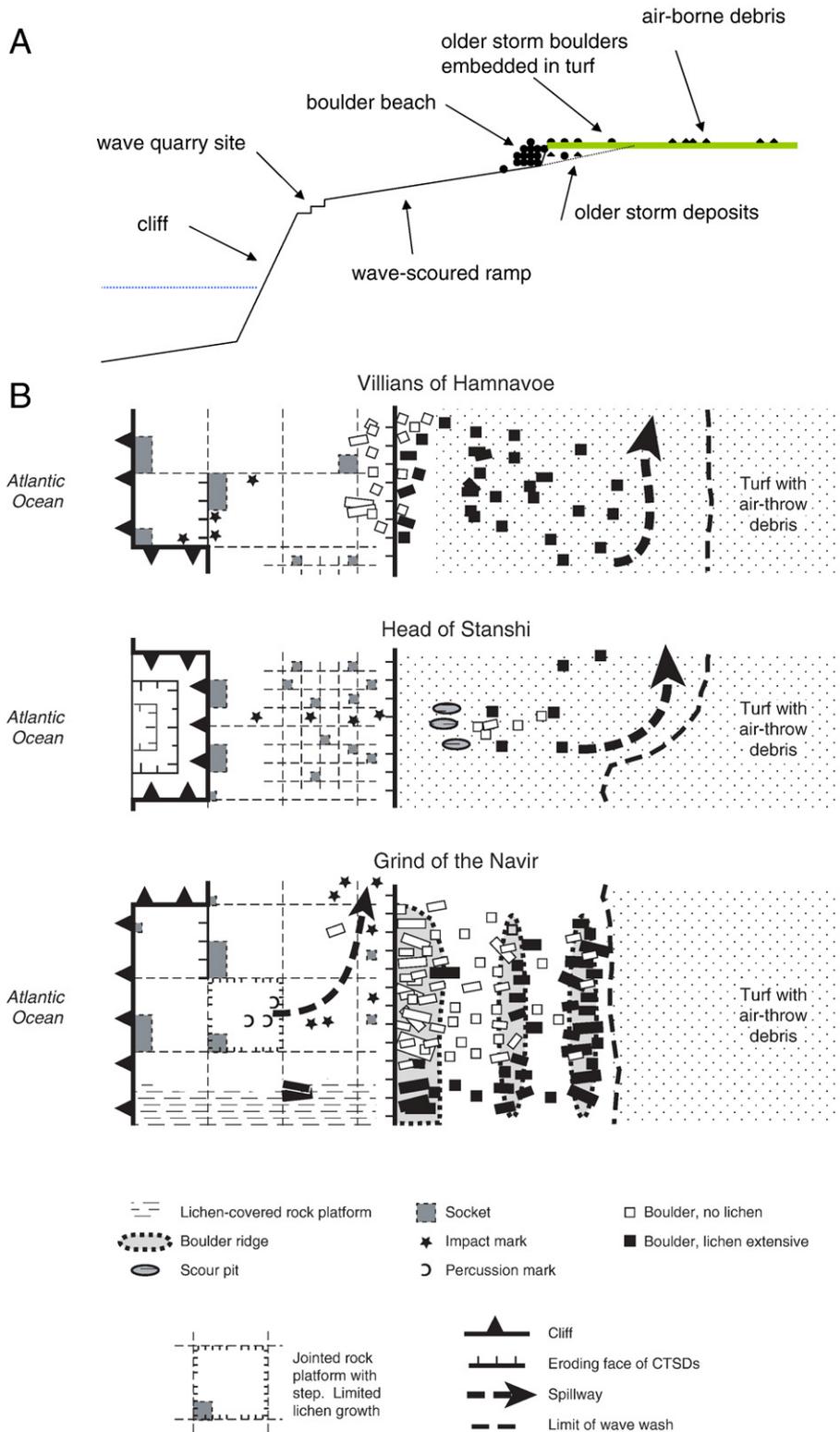


Fig. 4. Model of CTSD geomorphology. A. Schematic cross section. B. Schematic plans of features at key sites.

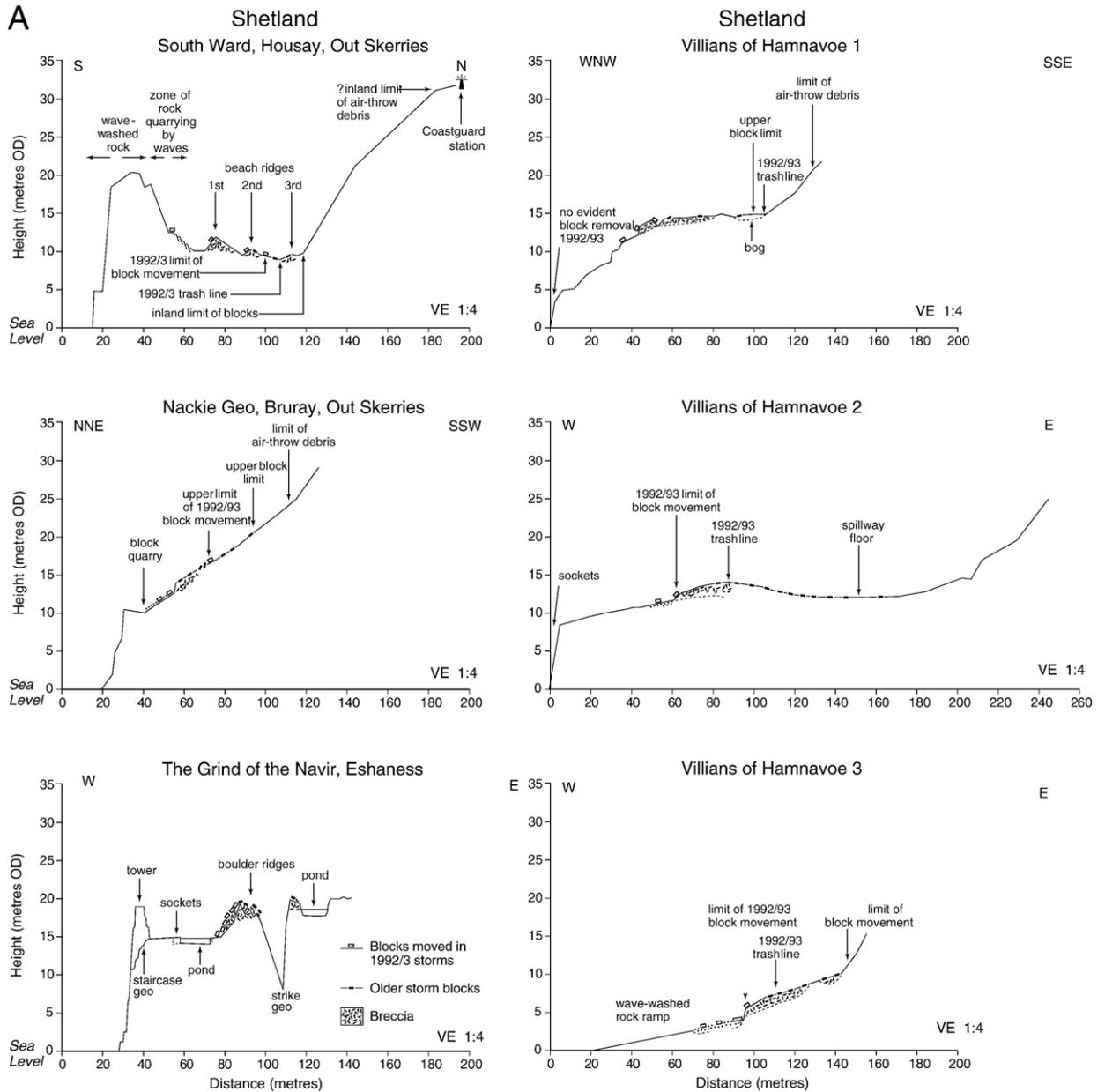


Fig. 5. Cliff transects. A. Shetland. B. Orkney and Caithness. C. Aran. VE Vertical Exaggeration.

also impound boggy depressions or ephemeral lochans. In North Rona, at Villians of Hamnavoe and on most parts of Aran, the cliff-top platform or ramp is backed by a prominent, single, coast-parallel, asymmetric ridge, 1–4 m high, with a steep, often undercut seaward face and a gentler landward slope, that may be locally turf-covered. Evidence of boulder quarrying by waves may be seen locally at the base of the ridge after storms but often the base of the ridge is masked by boulders fallen from above (Fig. 9). Beyond the wave limit of recent

storms in the Northern Isles, isolated boulders, imbricate boulder clusters and boulder spreads lie on relatively gently-sloping and turf-covered platforms or ramps. At Villians of Hamnavoe, boulders occur up to 90 m inland of the limit of modern wave wash (Figs. 3B and 10B). At Head of Stanshi, wave-dumped debris emplaced on turf during the storm of 1/1/1992 has been mapped up to 50 m inland of the eroding edge of older CTSDs (Hall et al., in press). Excavations within shallow peat deposits at The Grind and elsewhere have

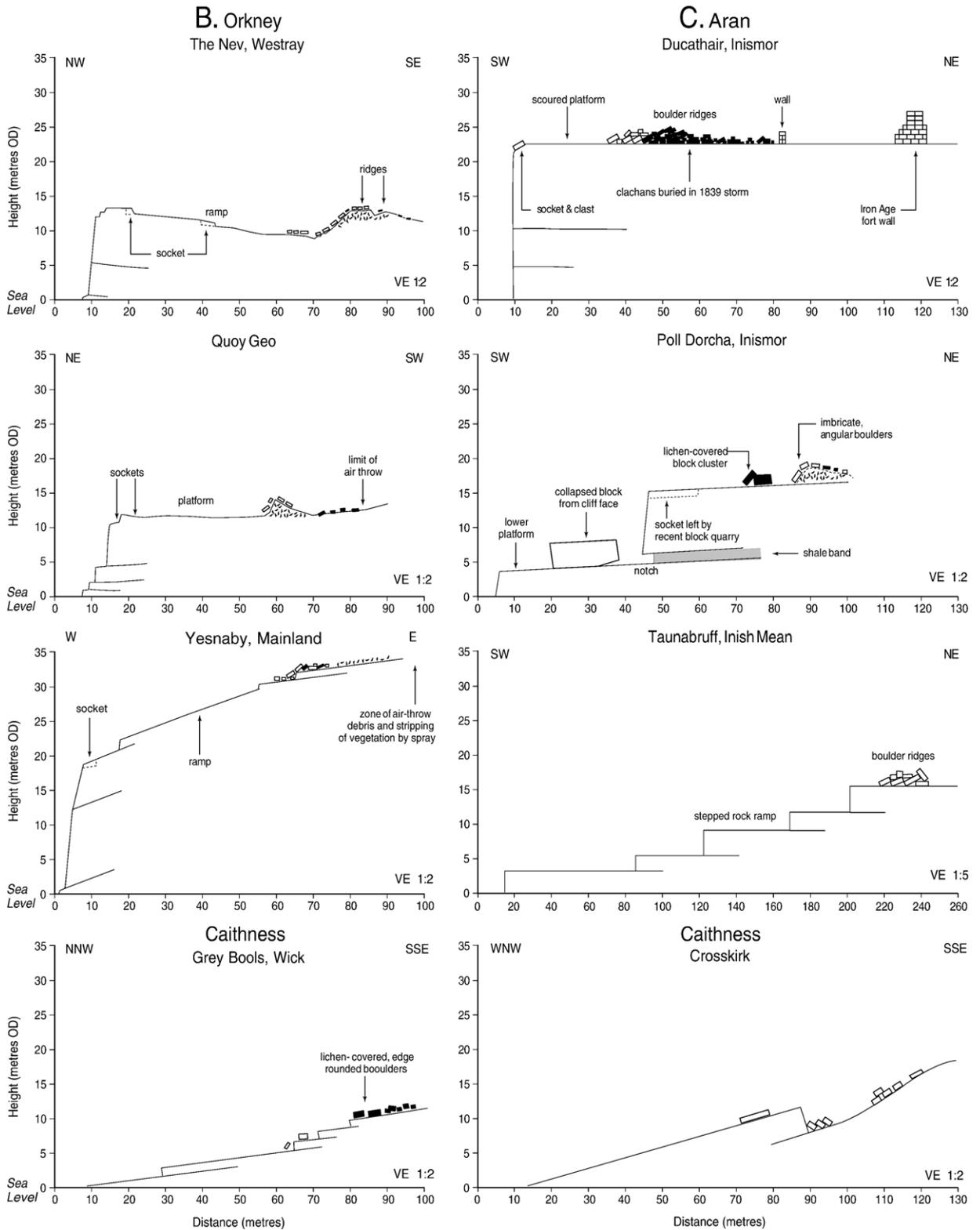


Fig. 5 (continued).

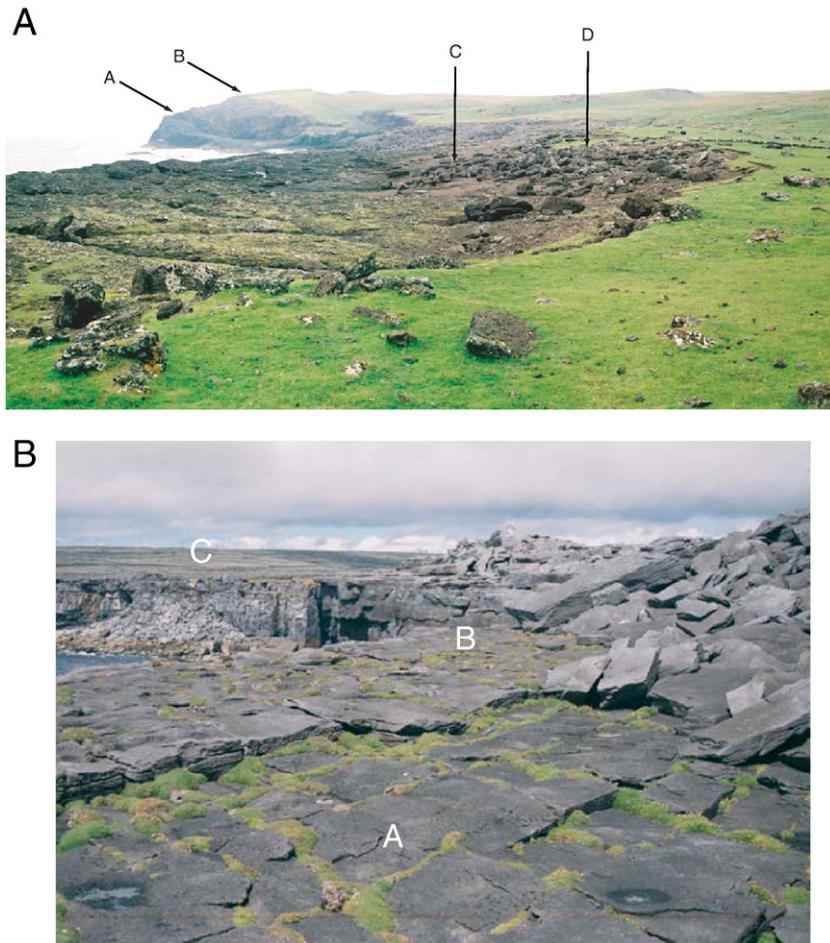


Fig. 6. A. Villians of Hamnavoe, looking north to South Head. Cliff in the background developed in andesitic tuffs, with ramp (A) at the junctions with the less resistant lavas. Limit of recent wave wash marked by turf edge (B), reaching 42 m OD on South Head. Recent storm boulders scattered to rear of ramp (C), with older, lichen-covered boulders to the rear (D). In the foreground, lichen-covered boulders lie partly buried in the turf. B. Inish Mór. Eroding cliff-top ramp at 15 m OD. The ramp retains a partial cover of vegetation (A) and the eroding edge of the CTSDs extends to the cliff edge (B). A recent rock fall with lichen-free blocks is seen in the background (C).

revealed partly and wholly buried isolated boulders. These boulders appear to have been deposited by wave wash onto the bog surface and then buried as peat accumulated.

The CTSD ridges are usually arcuate in planform and mirror the plan intricacies of the cliff edge in front, with imbricate boulders generally conforming to this alignment. Locally, however, as at The Grind of the Navir and Villians of Hamnavoe in Shetland and in Inish Mór on Aran (Williams and Hall, 2004), there are clear differences in the alignment of the active ridge and of the boulder clusters in front, implying that either different directions of wave approach are involved in boulder transport or that cliff planform has changed since the two groups of CTSDs were deposited. These contrasts are most evident on Aran where the rock platform narrows and is lichen-covered, suggesting that ridges may

be rendered inactive by changes in coastal configuration consequent on cliff retreat. Further evidence of rapid cliff retreat is provided by coast-parallel ridges which terminate on cliff edges at the margins of embayments, implying ridge formation prior to erosion of the embayment and a subsequent diminution of ridge forming behaviour (Williams and Hall, 2004). At a number of sites, CTSDs are contiguous with, but lie at a higher elevation than the modern storm-generated boulder ridge equivalents. In Mousa, Shetland, wave-transported CTSD boulders up to 1 m in *A*-axis length reach an elevation of 20 m OD on Green Head, whilst adjacent modern boulder ridges reach elevations of 5 m OD. At the northern tip of Inish Mór, Aran, around An Grióir, modern boulder ridges pass inland and upslope into progressively more angular CTSD deposits.

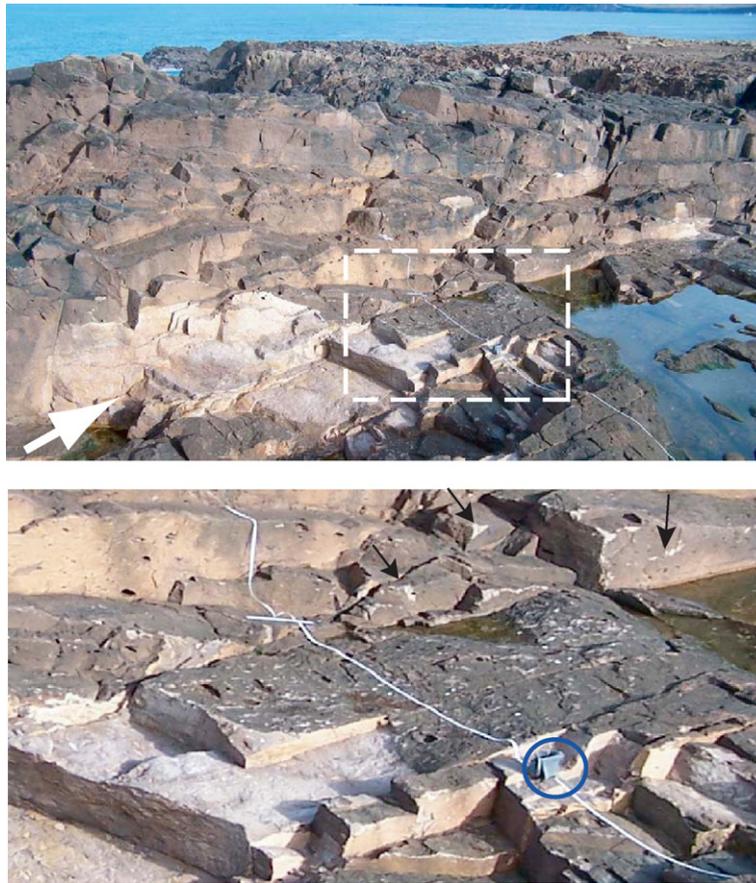


Fig. 7. Block removal and transport at The Grind of the Navir, Shetland, during the storm of 12/01/2005. Photo taken in February 2005 of the upper part of the staircase geo at 15 m OD. The top image shows sockets left by recent block removal and location of the detail below. The bottom image shows a range of impact and drag marks where the blocks have been moved across the cliff-top platform. Bag (circled) is 25 cm long. Arrow gives the direction of wave approach.

3.2.4. Spillways

At several CTSD sites, spillways are developed close to the upper limit of wave wash where wave water has exited landward or run parallel to the coast before exiting to the sea. On ramps overlain by regolith and friable rock, such as at Yesnaby in Orkney, returning wave water has incised dendritic systems of shallow gullies. Similarly, where wave wash overtops a low cuesta, as on Housay, Out Skerries (Fig. 3A) (Peach, 1864) and at Villians of Hamnavoe (Fig. 3B), strike-aligned spillways are locally developed which return water to geo heads within the neighbouring cliff line. On narrow promontories, wave overtopping can result in the incision of channels into bedrock which bisect the promontory, as has occurred through the peninsula of Fianuis in North Rona (Geikie, 1901). On Eshaness and Stroma, storm wave water reaches the heads of streams on dip slopes and enters the terrestrial drainage network.

3.2.5. Wave-splash and air-throw zone

Behind the cliff-top ridges lies a zone where there is no direct impact by waves but which may be exposed in storms to gusts of >240 km/h and to large volumes of sea water in wave-splash and spray. The cliff top may have been stripped of vegetation due to the effects of spray, wind and grazing by sheep to leave extensive deflation surfaces covered by clasts left by the winnowing of sandy till or weathered bedrock. Alternatively, the cliff top may retain a tenacious turf cover with widespread *Ameria maritima*. The turf may wholly or partly cover older gravel breccias. Scour pits may be evident towards the seaward edge of the turf, with the displaced debris deposited a few metres inland of the pit, suggesting erosion by water moving landward (Mac-taggart, 1999). More widely, the ground surface may be littered with angular, platy pebbles and small cobbles as individual clasts and spreads. The distribution of these sheets of surface clasts reflects the planform shape of the



Fig. 8. Cluster of imbricate limestone blocks at 20 m a.s.l. at Poll Dorcha, Inish Mór, Aran. The blocks have a partial cover of *Caloplaca marina* and have become isolated during retreat of the backing CTSD ridge.

cliffs, reaching up to 90 m inland in vales at the heads of geos and bays. Eroding banks of turf-covered gravel breccias up to 1 m thick composed exclusively of local flagstone occur on Westray, Orkney at or behind the edge of vertical cliffs. At these and other localities on Orkney and Shetland the absence of coarser debris and of scoured rock surfaces implies that these gravel breccias have accumulated above the elevation of wave wash. The distribution of the debris is consistent with air-throw during storms, with clasts projected skywards by waves breaking on the cliff face and top and then carried landward by very high winds.

3.3. Lithofacies

CTSDs are composed largely of locally-derived coarse clastic debris arranged as ridges, sheets, clusters and isolated clasts.

3.3.1. Boulder accumulations

Boulders are overwhelmingly angular and composed of the rock that forms the adjacent platform, together with rare glacial erratics reworked from till. Hence clast shape and size is largely controlled by the structure of the local bedrock. Tabular boulders tend to



Fig. 9. The Grind of the Navir, Shetland, in 2003. Boulder ridge to rear of cliff-top ramp. Note fresh boulders up to 1.8 m across thrown on to the front edge of the ridge during and since the 1991/2 storms. The ridge was emplaced in the 18th or 19th century.

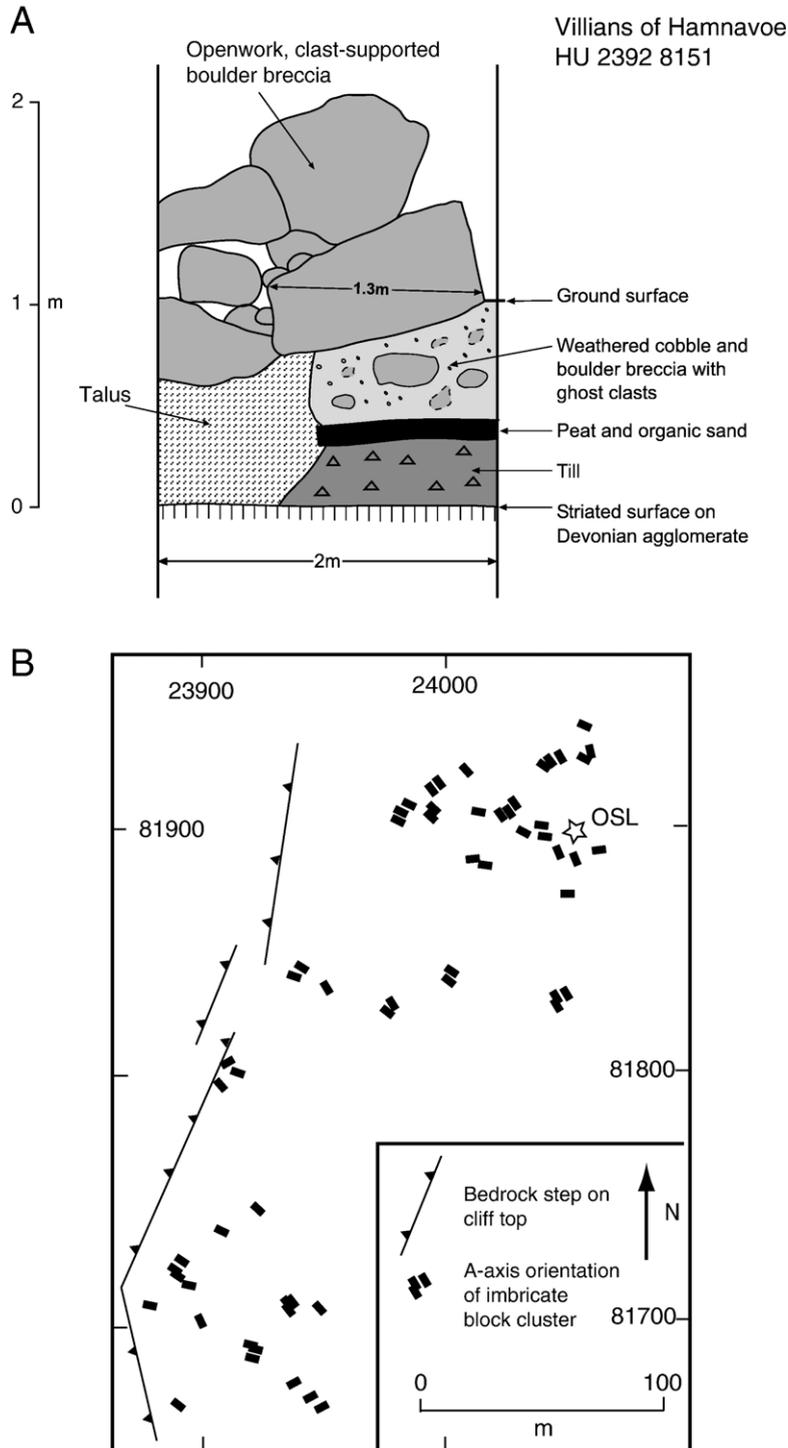


Fig. 10. A. Section in older CTSDs at Villians of Hamnavoe. B. Orientation of imbricate boulder clusters at Villians of Hamnavoe. Location in Fig. 3B.

dominate on schist, Devonian sandstone and Carboniferous limestone and cuboidal boulders on granite, gneiss and ignimbrite. In Aran, clast roundness increases towards sea level in response to more frequent

wave transport at lower elevations (Williams and Hall, 2004).

Clast sizes in CTSDs rarely reach the block category of >4 m B-axis (Blair and McPherson, 1999) and

boulder sizes dominate. Boulders also occur on lower platforms and are related to cliff collapse and low-level quarrying. These boulders may be moved by waves both landwards across low platforms or removed seawards (Williams and Hall, 2004) but since such boulders do not reach cliff tops they are not considered further here. *A*-axis lengths of boulders in CTSDs frequently exceed 1 m and reach 3 m. On the rear of the platform at Poll Dorcha, Inish Mór, boulders reach 18 m³, with *C*-axis length reflecting the depth of the bed of limestone from which the boulder has been quarried (Williams and Hall, 2004). Boulder size probably underestimates the maximum size of rock mass that can be quarried and transported because larger blocks tend to disintegrate during transport. Hibbert-Ware (1822) described the results of a storm in 1818 at Stenness, Shetland, where a block ~ 10 m³ was quarried and moved 9 m onshore before disintegrating into 13 or more pieces.

The seaward face of CTSD boulder ridges is formed of large imbricate and fitted clasts dipping to seaward. Fine examples are seen developed in Devonian sandstones at Ness of Burgi, Scat Ness, and Green Head, Mousa, both in Shetland, where they form low ridges parallel to the cliff edge. The largest boulders tend to occur on the seaward face and crest of the ridges. The seaward face of the ridges may carry recently quarried boulders, with fresh, lichen-free upper surfaces and sharp, unweathered edges. In contrast, the upper and landward faces of the ridge tend to be dominated by older, partly lichen-covered and more weathered boulders, with less frequent fresh or overturned boulders. Lichen-covered sandstone boulders in Caithness and Orkney CTSDs show more advanced edge-rounding, indicating longer exposure to weathering (Woodman-Smith, 2004).

The boulders are preferentially aligned normal to ridge orientation. On straight sections of the southwest coastline of Aran clast orientation is towards 250°, the principal wave direction (Williams and Hall, 2004). In Shetland, different parts of the coast between Eshaness and South Head are exposed to storms from the southwest to north. Clast orientation varies from 275–315°, suggesting that this coast may hold a record in its CTSDs of storm waves from a range of directions.

At sites with multiple ridges, sections in the eroding face of the seaward ridge show a maximum thickness of 4 m of CTSDs. The CTSDs are coarse gravel and boulder breccias which dominantly comprise clast-supported, angular gravels and boulders, often openwork near the ground surface, but with a matrix of sand and gravel in the voids at depth (Figs. 10A and 11). Measurements within CTSD breccias at 8 sites on Shetland indicate that no strong internal fabric is developed. At The Grind of the Navir and Clettnadal, Shetland, the matrix very occasionally includes a shell hash derived largely from water-line colonies of the mussel, *Mytilus edulis*. A range of other material may be firmly embedded amongst and beneath large boulders on the crest and landward slope of the ridges, including fragments of seaweed, sawn wood, fishing floats (cork, rubber and plastic), and, abundantly, plastic, polystyrene and foam rubber. Occasional sections in eroded older ridges, with lichen-covered blocks and weathered clasts, show no plastic debris (Fig. 10A).

At sites with a single CTSD ridge, boulder spreads may continue up to 100 m inland. Boulders 0.1–2.0 m long rest on or are embedded in the modern turf (Fig. 6A). On part of the Villians of Hamnavoe, Shetland, the blocks have a preferred orientation towards the NW but



Fig. 11. Section in CTSD breccia on Inish Mór.

crossing alignments suggest deposition by multiple events (Fig. 10B).

3.3.2. Gravel spreads

The turf behind the ridge often grows on a thin surface layer of sandy granule and pebble gravel. This rests on up to 210 cm of crudely flat-bedded, angular pebble and cobble gravel, with occasional boulders. These back-ridge breccias thin inland and include 2–20 cm thick layers of sandy coarse gravel of similar characteristics to that immediately below the turf but apparently lacking in organic material. Thin lenses of organic sand representing former soil surfaces also occur at a few sites. At Villians of Hamnavoe, Shetland, and Yesnaby and The Nev, Orkney, the basal parts of the breccias both beneath and behind ridges are weathered, with partial decomposition of tuff and sandstone clasts and development of a clay silt matrix component.

Sections in the eroding seaward faces of the ridges show that the breccias may rest on till or directly on bedrock (Fig. 10A). In places, however, thin soil profiles underlie the breccias, probably representing older turf layers immediately prior to the onset of deposition. At The Grind of the Navir and Clettnadal, Shetland (Whittington et al., 2003; Robinson, 2004), fine-grained pond deposits are found beneath the erosive base of the storm breccias, implying that subsequent cliff retreat has caused drainage of pre-existing ponds.

The turf behind the ridges often carries spreads of platy clasts. Transects normal to the coast from the turf edge were undertaken at Villians of Hamnavoe 5 months after the major storm of 1/1/1992 (Fig. 12), when recorded wind speeds reached 242 km h^{-1} in gusts on northern Shetland. The surveys revealed isolated and clustered clasts (mean *B*-axis length 43 mm, $n=324$) resting on turf that was still green. These clasts had been moved during the recent storm and yet lay up to 91 m inland of the trash-line that marked the upper limit of wave wash. Air-borne transport of new coarse clastic debris in wind-driven spray is indicated, together with wind-driven movement of previously deposited clasts.

Breccias above vertical cliffs beyond the limit of wave wash on Westray comprise parallel-bedded sandy gravel with angular, platy pebbles of local flagstone. Bedding conforms to the detail of the local slopes but clast orientation is varied. Although the breccias rest on weathered till, the breccias do not contain cobbles and boulders, glacial erratics have not been observed and the breccia matrix is less weathered, implying that the till is not the primary source for the breccia debris. A source local to the cliff top on which the breccias rest is required and the cliff face is the only nearby exposed rock surface.

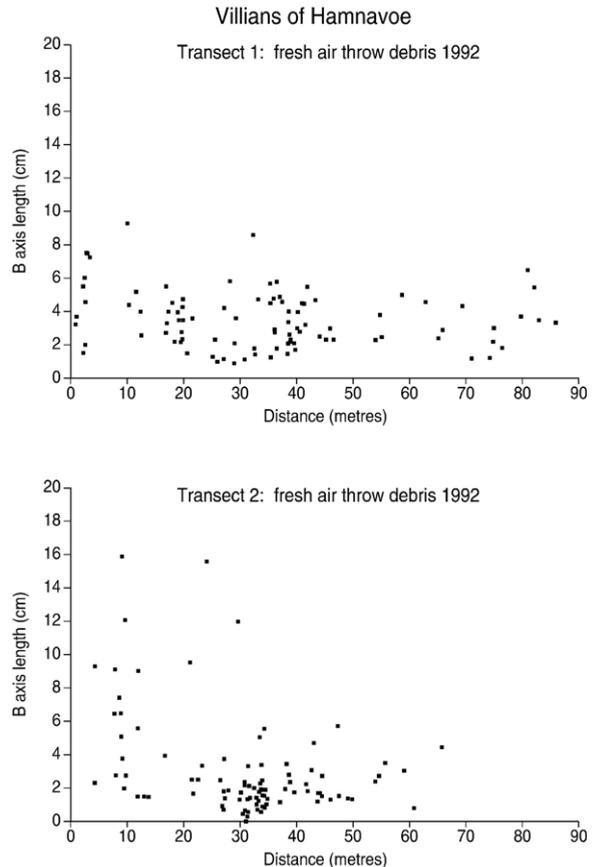


Fig. 12. Plots of clast size against distance of wave-splash and air-throw debris from the 1/1/1992 storm at Villians of Hamnavoe. Distances are measured landwards from the edge of the turf at the rear of the rock platform (Fig. 3B).

The rear of cliff-top platforms and also cliff tops without platforms may carry eroding banks of turf-covered breccias composed largely of angular, platy pebbles with variable amounts of sand matrix. The breccias rest on and include sandy organic layers that mark former soil horizons. These breccias represent older accumulations of air-thrown and water moved debris. Clast lithology indicates that the debris has been sourced from the cliff face and the cliff-top platform.

4. Origins of CTSDs

Along the coastlines of Scotland and Ireland, CTSDs appear to be largely restricted to cliffs that plunge into deep water. This distribution, together with the considerable heights reached by waves impacting on these cliffs indicate that these sites receive unusually large waves that have not lost energy or height in moving

through shallow water. Nevertheless, it is important to examine alternative modes of emplacement before expanding on any storm wave driven mechanism. Two potential alternative origins seem possible: that the CTSDs represent emerged marine features elevated by isostatic uplift, or that tsunami waves are responsible for their emplacement.

4.1. CTSDs as emerged marine deposits?

Unlike much of the Scottish mainland coast, the coasts of Shetland and Orkney have been dominated by submergence over much of the Holocene (May and Hansom, 2003) and evidence for emergence is absent. Elsewhere, undisputed evidence for emergence is sparse with suggested emerged beaches being confined to low elevations close to sea level in Caithness (Dawson and Smith, 1997), the Outer Hebrides (Shennan et al., 2000) and Galway Bay (Mitchell, 1976). Consequently, the occurrence of CTSDs at elevations of 10–40 m above present sea level in those peripheral areas of the British Isles that lie well outside of the zero isobase for Holocene relative sea level changes (Shennan and Horton, 2002) strongly suggests that they are not attributable to changes in sea level.

4.2. CTSDs as tsunami-genic deposits?

Much of the literature on the emplacement of megaclasts at various altitudes on shores relates to the impact of tsunami (Bryant, 2001; Nott, 2004; Noormets et al., 2004). Indeed, imbricate piles of boulders at altitude and distance from the coastal edge, together with shell and debris inclusions, are noted by Bryant (2001) to be one of the diagnostic signatures of tsunami, particularly in the Pacific and Caribbean. However, the tsunami record in the Northeast Atlantic is extremely sparse. For example, during the Holocene Scotland was affected by only 3 known tsunamis between 8000 and 1500 years ago (including the large Storegga tsunami) (Bondevik et al., 2005). The only substantial known historical tsunami in the Northeast Atlantic resulted from the Lisbon earthquake of 1755, this producing waves reported at no more than 2 m high in Scotland and Ireland. Even the Grand Banks tsunami of 1929, which produced a 30 m high wave close to the Canadian coast, had no reported effect in Europe (Dawson, 2000). In modern times there are no reports of tsunami affecting the Northeast Atlantic coast and so it seems unlikely that tsunami are either frequent or large enough to have any substantive impact on coastal processes in the study area.

4.3. CTSDs as storm wave deposits

Since CTSDs are unlikely to be emerged or tsunami-genic features, then questions of the origins of CTSDs focus instead on recent storms and the generation, movement and emplacement of individual boulders, together with the mechanisms for accumulation, erosion and recycling of the breccias beneath and behind ridges.

On rock coasts, new boulders are mainly generated by cliff collapse, often the result of undercutting as well as by bedrock quarrying in the breaking wave zone (Trenhaile, 2002; Kogure et al., 2006). Accessible examples of boulders generated by cliff collapse occur on Inish Mór, Aran (Fig. 6B). At An Grióir, a large collapse involving boulders up to 4 m *A*-axis length probably postdates a recent detailed description of the coastline (Robinson, 1990). At South Head, Shetland, a cliff failure involving 2138 m³ of rock including individual boulders of up to 7 m *A*-axis, occurred onto a sloping rock ramp below the cliff between 1996 and 1999 but had been completely removed by wave activity by 2003. However, cliff collapse is relevant only as a contributory process to CTSDs on cliffs with a stepped profile. Elsewhere rockfall debris from the cliff face is removed from the base of the cliff. More generally, cliff-top platforms lack backing rock faces to act as sources for blocks.

On vertical cliffs with upper platforms or ramps, the source of CTSD boulders is indicated by scars and sockets on the cliff top. Inspection of the lower cliffs of Eshaness shows a general absence of scars, with extensive cover of the black, spray-zone lichen *V. maura*. Occasionally, scars occur on parts of the lower and middle cliff but prominent scars and sockets occur much more frequently at the apex of the cliff-top and on the seaward edges of steps on the cliff-top platform or ramp. These quarrying scars and sockets are often wholly or partly free of a weathering patina or lichen cover, indicating recent boulder removal (Fig. 7). The CTSDs are also composed almost exclusively of clasts of identical lithology to that of the cliff-top.

Boulder transport requires detachment, lift and carry. Opportunities for detachment are enhanced along joint and bedding surfaces and well-developed CTSDs are favoured by rocks with well defined joint and bedding planes. Such structural conditions occur in the Carboniferous limestone of Aran and in the Devonian ignimbrite at The Grind of the Navir, where chock stones of up to 15 cm *C*-axis have been observed jammed into open horizontal fractures. The injection into joints and bedding planes of water and air under high pressures is indicated as a mechanism of lift, and although the total amount of lift is unclear, it must exceed

the maximum thickness of the chock stones. At Poll Dorcha, the bedding planes bounding the mega-socket described above are 1.4 m apart and control the *C*-axis size of the fragmented boulders at the rear of the ramp. Since the original block, either whole or already fragmented, was transported 32 m to landward (Williams and Hall, 2004), it must have been lifted from its socket by at least 1.4 m in order to surmount the bedrock step marking the quarried edge of the next bedding plane.

Boulders at this site and others in Aran and Shetland are also inverted. Where the inverted boulder lies adjacent to a socket of matching geometry, it is clear that the boulder has been rotated in the process of lift. Where the inverted boulder lies on the seaward face of the CTSD ridge then it is also possible that the boulder was rotated by wave interaction with the ridge. In addition, saltation of these boulders during transport is implied by the occasional presence of chatter marks on the upper limestone ramps on Aran (Williams and Hall, 2004) and by trails of impact marks and chipped edges visible on otherwise weathered and lichen-covered surfaces, such as those at The Grind (Fig. 7). Hansom et al. (in press) provide modelled solutions for the forces of wave impact and subsequent lift at this site, demonstrating that such forces exceed those required to fracture, lift and transport of boulders of the sizes observed at this and other CTSD sites.

Flow velocities across cliff-top ramps also need to be sufficient to remove boulders of $< 6 \text{ m}^3$ in volume. The depth of water crossing the upper platforms during recent storms cannot be greater than the difference between the platform height and the top of the 2–6 m high boulder ridges, as at many sites the rearmost ridge lies close to the inland limit of wave-transported debris. The emplacement of boulders on the crest of the ridge implies a bore of water moving at sufficient velocity to carry boulders of $> 1 \text{ m}^3$. Modelling indicates that a cliff-top wave of 5 m height is capable of producing a bore of 14 m s^{-1} maximum and 7 m s^{-1} mean velocity over the cliff-top ramp (Hansom et al., in press) and capable of travelling upslope over distances of $\geq 50 \text{ m}$ to emplace boulders on the rear of the ramp. At Virda Field, Papa Stour, the ramp is 60 m wide and slopes 10° to seaward above a 20 m high cliff, with boulders marking the upper limit of wave influence at 35 m OD; on Inishmaan, the ramp is 200 m wide and boulder ridges reach an altitude of 50 m asl. These flow depths and velocities are similar to those estimated for possible tsunami waves on cliff-tops and platforms at up to 32 m asl on the coast of New South Wales (Young et al., 1996).

Many of the individual boulders in the boulder ridges may be recycled from earlier deposits since the seaward faces of ridges are actively eroded. Over-turned

boulders, with lichen and weathered surfaces on their undersides, occur occasionally in the cliff-top boulder ridges and also within boulder spreads and clusters behind the ridges. Frontal erosion of the ridge removes boulders, together with any gravel matrix within the ridge that might occur, leading to localised collapse of the ridge face. Small boulders may also be quarried directly from the bedrock at the base of the ridge. In Inish Mór, landward migration of the boulder ridge appears to be generally in step with retreat of the cliff face, as zones with narrow cliff-top platforms show signs of rapid frontal erosion of the ridge and landward movement of the crest. In Orkney and Shetland, advance of the boulder ridges often occurs across older, weathered breccias formed of a combination of debris from older storm deposits and from wave splash and air-throw. This landward shift is directly analogous to the landward migration of conventional storm beach ridges at lower elevations.

Many ridges show a contrast between an openwork and very coarse breccia on the surface of the ridge and a clast-supported, more densely-packed and smaller calibre breccia below. In a few places, such as at The Grind, the local presence of a densely-packed shell hash within angular gravel breccia and packed into the voids between larger boulders suggests local deposition by sediment-rich water. It is also likely that the openwork breccia is progressively in-filled during subsequent storms by pebbles, granules and sand from wave splash and air-throw. The movement and vibration of boulders during major storms may also favour the downward migration of smaller clasts.

Inland of boulder ridges that show eroding ridge faces, boulder spreads are characterised by imbricate clusters that indicate rapid sheet flow of water that has penetrated beyond the ridge. At Villians of Hamnavoe, these boulders are lichen-covered and appear to relate to relatively old storms but similar spreads were found distributed over part of The Head of Stanshi following the storm of 1/1/1992 (Hall et al., in press).

Landward of the wave-washed zone is an extensive zone of wave-splash, spray and deflation. It is commonly marked by extensive areas that have been stripped of vegetation and soil cover and displays the local development of eroded terrace edges and scour pits. Where reverse slopes occur behind the cliff top, draining sea water may cut spillways that intersect with the landward drainage pattern and stream heads.

Breaking waves at cliffs project water and coarse debris into the air which is then transported landward by high winds. Images of spray over cliffs during storms, anecdotal evidence from Eshaness that the roof of the lighthouse at $\sim 55 \text{ m OD}$ has had to be repeatedly

cleared of cobbles and boulders after major storms in the last century and more widespread accounts of damage to lighthouses, including Muckle Flugga light at 66 m OD, and other buildings on top of cliffs (Bathurst, 1999) indicate that debris can be projected during storms high above the cliff top. The inland limit of air-thrown debris during storms is not known but probably far exceeds the 80 m distance recorded for 6 cm pebbles in the 1992 storm in Shetland. In the zone of wave-splash and air-throw, clasts up 0.2 m in *B*-axis diameter commonly litter the ground. The clasts may be gradually buried after deposition by growth of the turf to form deposits of gravel breccia on the cliff top. Alternatively, the clasts may roll or slide inland under high wind speeds in subsequent storms. Air-borne storm debris undoubtedly reaches cliff-top lakes but its signature has yet to be elucidated (Robinson, 2004).

5. Age

5.1. Recent observations

On Shetland, surveys after the major storms of 1/1/1992 and 17/1/1993 identified fresh bedrock scars, impact marks, together with overturned boulders and new deposits of debris at the upper limit of wave wash. This allowed the upper limit of wave wash to be established at many CTSD sites, together with the largest blocks moved (Table 1). Although these storms generated mean hourly wind speeds of 111 and 117 km/h, two of the five highest recorded at Lerwick by the Meteorological Office between 1931 and 2005, the limits of wave wash usually lay within the landward limit of CTSDs (Table 1). The boulder sizes moved were also smaller than those mobilised in earlier storms. Lichen-covered CTSDs must thus relate to older, more severe storms.

5.2. Photographic evidence

Photographic evidence from The Grind of the Navir, Shetland (Hall et al., in press), and The Nev, Westray (Crampton and Carruthers, 1914) also records the quarry and transport of large blocks at intervals from 1900 onwards. The CTSDs on Shetland and Aran locally include and bury a range of man-made debris (Hansom, 2001; Williams and Hall, 2004) which provides a minimum age for the boulders that surround and entrap the debris. For example, cork floats dating from around 1920, plastic floats and other jetsam from around 1940, and inflatable buoys dating from around 1970 can be found deep within the boulder ridges and are thus coeval with the emplacement of the boulders. Historical accounts

record boulder movement at both Irish and Scottish sites in the 19th century (Hibbert-Ware, 1822; Stevenson, 1845; Peach, 1864; Kinehan et al., 1871; Robinson, 1990).

5.3. Relative age criteria

Whereas it is clear that many ridges and CTSDs have been modified by very recent wave and storm activity, it is also apparent that many have been in place for some time. In Inish Mór, isolated lichen-covered block clusters on the cliff-top platform have been tentatively linked to a major storm in 1839 when waves dumped boulders on to the Black Fort, constructed \sim 2500 BP, at 30 m asl (Williams, 2004; Williams and Hall, 2004). On Shetland, the CTSDs at Eshaness and Out Skerries are described in 19th century accounts (Hibbert-Ware, 1822; Peach, 1864).

Lichen-cover indicates a residence time of a minimum of several decades. *V. maura* is characteristic of extremely exposed rock shorelines in the North Atlantic (Dalby et al., 1978) and its cover is a useful indicator of the recent stability of rock surfaces subject to frequent spray on cliff faces and cliff top. Development of >50% cover of the black, tar-like covering of this lichen takes \geq 70 years at The Grind (Hall et al., in press). Scars and sockets with limited or no cover of *V. maura* were exposed by erosion <70 years ago at this site. Similarly, scars and sockets without *Caloplaca* and *Lecanora* were exposed < 20 years ago.

Comparison of edge rounding of sandstone boulders in CTSDs with that of gravestones of similar lithology suggest that lichen-covered CTSD accumulations at The Nev and at Wick date from a stormy period in the early 19th century (Woodman-Smith, 2004). Near to the latter site, concrete blocks weighing 726 and 2359 kg were removed from the former harbour breakwater in storms in the late 19th century but the CTSDs of the Grey Boals at Wick were described by Hugh Miller (1841) and by Charles Peach in 1864 (Geikie, 1887) and so predate these storms.

5.4. Luminescence and radiocarbon dating

The age of older CTSDs related to extreme storms prior to the 20th century is more closely constrained at only two localities on Shetland. At The Grind, separate samples of shell hash have yielded radiocarbon ages suggesting emplacement of the main boulder ridge (Fig. 9) between the 18th and 19th centuries (Table 2). At nearby Villians of Hamnavoe, the OSL age of the uppermost sands beneath surface boulders to the rear of the cliff-top ramp at two sites (SUTL-691 and 694) suggest earlier emplacement at some time between the

Table 2
Results of dating from CTSD sites on Shetland

Location and Grid Ref.	mOD	Material	Site	Laboratory code	Age BP	Calibrated age (AD)
Grind of the Navir 1	17.5	Mixed shell	Within first boulder ridge at rear of cliff-top platform	SUERC-4829 (GU-12470)	565±35 ¹⁴ C yrs	1780–1810
Grind of the Navir 2	18	<i>Mytilus edulis</i>	Within first boulder ridge at rear of cliff-top platform	SUERC-6448 (GU_13010)	510±35 ¹⁴ C yrs	1720–1880
Villians of Hamnavoe 1 HU 24052 81901	16.5	Sand	Below surface boulder A, in eroded terrace, rear of cliff-top ramp	SUTL-691	370±160 OSL yrs (yrs before 2000 AD)	1630±160
Villians of Hamnavoe 1 HU 24052 81901	15.8	Sand	Ca. 0.7 m below surface boulder A, directly beneath buried boulder B, in eroded terrace, rear of cliff-top ramp	SUTL-693	1113±123 OSL yrs	887±123
Villians of Hamnavoe 2 HU 24041 81900	16.3	Sand	Below surface boulder in eroded terrace, rear of cliff-top ramp	SUTL-694	385±70 OSL yrs	1615±70

Note: In [Sommerville et al. \(2003\)](#), the location of SUTL-691 was wrongly labelled as Grind of the Navir.

15th and 18th centuries ([Fig. 13](#)). More deeply buried sands (SUTL-693) suggest even earlier emplacement between the 8th and 11th centuries. These dates are considerably younger than any known or postulated Holocene tsunami layers identified in Shetland ([Bondevik et al., 2005](#)).

5.5. Comparisons with regional sea level histories

Modelling of Holocene sea levels constrains the maximum age of these features on Shetland and Orkney. For example, [Lambeck \(1993\)](#) models sea level at 5000 BP to be at –10 m OD and this places many of the presently active cliff tops beyond the reach of even the

largest waves. Indeed, in Orkney and Shetland relative sea level rise over the late Holocene, together with present rates of sea level rise ([Dawson and Smith, 2001](#)), can be used to suggest that the boulder ridges and CTSDs are accessed by storm waves at increasingly frequent intervals as a consequence of nearshore deepening. A similar argument can be advanced for the Aran Islands ([Williams and Hall, 2004](#)).

6. Discussion

At all of the CTSD sites reported here, erosion of the cliff face and, especially, the cliff top is clearly linked to the accumulation of CTSDs landward of the cliff. At

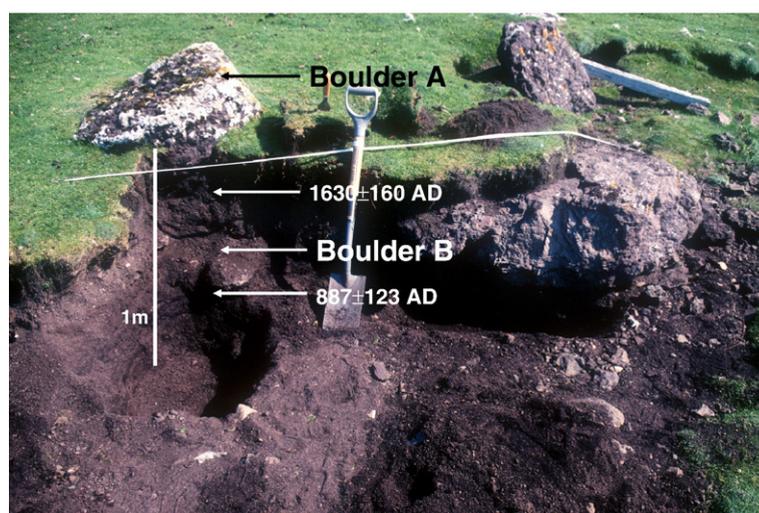


Fig. 13. OSL sample site at Villians of Hamnavoe. The site lies to the rear of the gravel and sand sheet on the cliff-top platform at HU 24052 81901 at an elevation of 19 m OD. Adjacent partly-buried and lichen-covered boulder clusters of probable similar age to the upper block show *A*-axis orientations towards 324° and 335°, suggesting wave approach from the NW.

altitudes of 10–50 m, erosion occurs only during major storms as only then can waves reach the cliff top. CTSDs generated and reworked during storms thus form an archive of information about the timing and intensity of storms and of directions of wave approach. Wind-driven spray has been recognised previously as an agent of sediment transport only on sandy coastlines (Jennings, 1967; Cooper and Jackson, 1999) but the presence of air-throw debris as part of CTSDs indicates that wind-driven spray may carry debris tens of metres landward of the cliff top. The maximum distance of transport inland of granule and sand debris is unknown but likely to be considerable.

The most striking feature of the CTSDs is the presence of displaced large boulder and blocks at elevations of up to 50 m asl. The liberation and transport of boulders and blocks is now recognised widely as a result of the impact of large waves on breakwaters (Stevenson, 1845; Cox and Cooker, 1999; Noormets et al., 2002) and shore platforms (Noormets et al., 2002; Noormets et al., 2004), as well as at higher elevations on stepped cliff faces and on cliff tops. The significant progress made in recent years in modelling the forces involved in fracture, lift and transport of large clasts indicate that rapidly-moving bores capable of quarrying and moving large blocks can be generated by breaking waves not only close to sea level (Cox and Cooker, 1999; Nott, 2003; Noormets et al., 2004) but also on cliff-top platforms (Hansom et al., *in press*). The effects of storm wave impacts therefore extend to elevations well in excess of those generally reported in the literature, although the configuration of the coast has a profound impact on the wave behaviour at the cliff face.

Much debate has focussed on the origins of megaclasts as the products of wave impacts in either cyclones or tsunami (Young et al., 1996; Nott, 2003; Noormets et al., 2004). Part of the difficulty in resolving such questions is that large wave impacts from either source tend to generate similar forms and deposits. However, the coasts of the British Isles lack a record of significant, recent tsunami activity (Williams and Hall, 2004) and the widespread evidence of recent and continuing activity during major storms requires that CTSDs are linked to mid-latitude cyclonic storms. The cliff-top boulder deposits and features are linked to the presence of large sockets, impact marks, mega-blocks and imbricate boulder clusters on cliff tops. These features are not exclusive to these coasts and have been associated elsewhere with wave impacts on cliffs during both tropical storms and tsunami (Young et al., 1996). Nor is clast size an effective discriminant. The 277 m³ rock mass quarried at Poll Dorcha is within the 100–1000 m³ range of the largest

clasts reported from tropical coasts (Bourrouilh-Le Jan and Talandier, 1985; Hearty, 1997; Noormets et al., 2002). Features that appear to distinguish CTSDs from tsunami deposits include the development of boulder ridges faced with imbricate blocks. The organisation of boulders into ridges may require repeated reworking by waves rather than the rare impact of a train of tsunami waves (Williams and Hall, 2004). In contrast, the development of boulder spreads with clusters of imbricate blocks can be the product of a single or a small number of wave impacts during either storms or tsunami. Boulder clusters are inherently more stable than isolated clasts and so may remain in place longer (Bishop and Hughes, 1989).

Wang et al. (2005) reported that the highest wave recorded during Hurricane Ivan in 2004 to be 27.7 m. This is directly comparable with the estimated 1-year maximum wave height of 24.3 m off Shetland in storms (Hansom et al., *in press*) and to a recent record of a 29.1 m high wave near Rockall (Holliday et al., 2006). It is likely that some of the landforms and deposits identified in the CTSD model (Fig. 4) also occur on sections of tropical and subtropical coasts subject to hurricanes that also possess deep water offshore and cliffs 10–25 m high. Nott (2004) notes that deposition of boulders by waves occurred on cliff tops on the Pacific island of Niue in 1991 and 2004 during intense tropical storms and mentions other localities subject to intense tropical cyclones with similar accumulations of boulders in the Southern Ocean and in parts of the Pacific, Indian and Atlantic Oceans. These accumulations appear directly comparable to wave-generated CTSDs but it is unknown if they are accompanied by air-thrown debris.

Traditional models of the evolution of marine cliffs emphasise the importance of breaking waves around high water mark. The development of notches due to the focus of erosion in this narrow zone leads to undercutting, cliff collapse and the extension of shore platforms (Kogure et al., 2006). On the extremely exposed cliffs of Orkney and Shetland, shore platforms are narrow or absent and the cliffs may be honey-combed by caves, geos and other hidden openings (May and Hansom, 2003). These large cliff cavities may extend many tens of metres inland and penetrate the full height of the cliff. Enlargement of the cavities eventually leads to collapse of part of the cliff face and to cliff retreat. Waves may impact on these cliffs anywhere between 0 and 40 m OD according to the sea state. The frequency of wave impact is reduced with elevation but the magnitude may not be, as cliff tops with CTSDs are only reached during major storms by the highest waves. Cliff collapse and retreat on these exposed cliffs thus appears to be largely a consequence

of processes operating within or on the cliff during storms when high effective air and water pressures are generated in caves, slots and fractures and blocks are quarried from the cliff surface.

7. Conclusions

The cliff-top storm deposits of the Atlantic coasts of the British Isles form a distinctive end member to the much larger group of coarse clastic storm features. The detailed configuration of the coast, particularly the size, height, orientation and form of the cliff edge and top, exerts a major control on the distribution, altitude, clast orientation and clast size of the cliff-top deposits. The CTSDs are typically located on high cliff tops on exposed, deep water coasts and are characterised by the presence of angular clasts > 1 m in diameter as boulder spreads or organised into cliff-top ridges. The debris within the CTSDs is sourced from the cliff edge and top and recycled as the boulder ridges migrate inland, changing orientation as cliff faces retreat. Air-throw debris is added to the CTSDs during storms but widespread mobilisation of boulders is mainly confined to detachment following wave impact in major storms.

The characteristics and distribution of CTSDs allow the basic properties of the waves that generate these boulder accumulations to be identified:

- The CTSDs require deep water offshore and full exposure to storm waves and limited nearshore attenuation.
- The waves are capable of overtopping cliffs 10–30 m high and generating slam forces on the cliff top and cliff-top platform sufficient to fracture, detach and lift fracture-bounded boulders from between 1 and 40 m³ in size and, occasionally, as large as 277 m³.
- Platforms and ramps on the cliff-tops are swept by wave-derived bores of water parts of which can move at up to 14 m s⁻¹ (mean velocity 7 m s⁻¹) whilst transporting boulders of up to 40 m³.

The approach and impact of these extreme waves on the Shetland cliffs and the cliff-top transport mechanisms have been modelled successfully using field data and in scaled wave tank experiments on model cliffs (Hansom et al., *in press*).

The quarrying of large, fracture-bounded clasts from the cliff-top platform, especially from steps, can be related directly to the impact of waves in historic and recent storms. Block removal mirrors that recorded elsewhere from man-made structures (Stevenson, 1845) and shore platforms (Noormets et al., 2002) closer to sea

level. Although the size of mobilised boulders recorded to date in CTSDs in the British Isles is less than the largest attributed to tsunami, great storms and hurricanes in other parts of the world, this may be little more than a reflection of the tendency for jointed blocks to disintegrate into smaller boulders during wave transport. This suggests that wave-generated tractive forces operating at altitude on exposed cliff tops in the British Isles during large storms are equivalent to those associated with extreme wave-generating events at sea level anywhere in the world.

CTSDs also can be seen as a valuable and perhaps unique archive of data on the influence of extreme storm waves in the geological record. Existing dating evidence is limited but points to initial formation of CTSDs on Shetland within the last 1200 yr and continuing modification, particularly during and since the Little Ice Age. The presence of buried sand layers, shell hash and boulders within peat bogs to the rear of the cliffs reported here invites a detailed dating programme aimed at resolving the magnitude and frequency of extreme storm wave impact on cliffs on the Atlantic coasts of the British Isles. Moreover, CTSDs are likely not confined to the coasts of the British Isles and similar deposits may exist on many hard rock coasts around the world where high storm wave energy environments and deep water offshore co-exist with well-jointed and-bedded hard rock cliffs with upper platforms or ramps.

On these extremely exposed coastal sites cliff evolution does not fully conform to traditional models. Storm waves may impact on cliffs up to 50 m above sea level, removing blocks from the face and top of the cliff, with apparently limited erosion of the base of the cliff face. It is also possible that block loss within cavities such as caves and geos occurs during the same impacts of extreme waves that produce CTSDs but the extent of these cavities and the nature, frequency and rate of these processes remains largely unknown.

More speculatively, in such exposed locations it is possible that cliff collapse and retreat is related to wave events that modify the base of the cliff at lower recurrence intervals than those that remodel the cliff top and cliff-top platform, or that the impact pressures experienced at the base during major storms are less than those experienced at the top. It follows that the exact evolutionary relationship of cliff base to cliff top in such locations remains to be fully elucidated.

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