

Article

Using Ground-Penetrating Radar (GPR) to Investigate the Exceptionally Thick Deposits from the Storegga Tsunami in Northeastern Scotland

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Abstract: A submarine landslide on the edge of the Norwegian shelf that occurred around 8150 ± 30 cal. years BP triggered a major ocean-wide tsunami, the deposits of which are recorded around the North Atlantic, including Scotland. Ground-penetrating radar (GPR) was used here to investigate tsunami sediments within estuaries on the coast of northeastern Scotland where the tsunami waves were funnelled inland. Around the Dornoch Firth, the tsunami deposits are up to 1.6 m thickness, which is exceptionally thick for tsunami deposits and about twice the thickness of the 2004 IOT or 2011 Tohoku-oki tsunami deposits. The exceptional thickness is attributed to a high sediment supply within the Dornoch Firth. At Ardmore, the tsunami appears to have overtopped a beach ridge with a thick sand layer deposited inland at Dounie and partly infilled a valley. Later, fluvial activity eroded the tsunami sediments locally, removing the sand layer. At Creich, on the north side of the Dornoch Firth, the sand layer varies in thickness; mapping of the sand layer with GPR shows lateral thickness changes of over 1 m attributed to a combination of infilling an underlying topography, differential compaction, and later reworking by tidal inlets. Interpretation of the GPR profiles at Wick suggests that there has been a miscorrelation of Holocene stratigraphy based on boreholes. Changes in the stratigraphy of spits at Ardmore are attributed to the balance between sediment supply and sea-level change with washovers dominating a spit formed during the early Holocene transgression, while spits formed during the subsequent mid-Holocene high-stand are dominated by progradation.

Keywords: tsunami; estuary; sand layer; erosion; geophysical survey



Citation: Bristow, C.S.; Buck, L.K.; Shah, R. Using Ground-Penetrating Radar (GPR) to Investigate the Exceptionally Thick Deposits from the Storegga Tsunami in Northeastern Scotland. *Remote Sens.* **2024**, *16*, 2042. <https://doi.org/10.3390/rs16112042>

Academic Editor: Magaly Koch

Received: 14 March 2024

Revised: 8 May 2024

Accepted: 20 May 2024

Published: 6 June 2024



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1. Introduction

In the North Atlantic Ocean, tsunamis are low-frequency, high-magnitude events, their occurrence is rare, there are few instrumented records, and historical accounts are very sparse [1]. Consequently, our knowledge of North Atlantic tsunamis is almost entirely based on the sedimentary deposits that have been left behind. The Storegga slide in the North Atlantic is one of the biggest recorded submarine landslides, covering an area of $95,000 \text{ km}^2$, an area larger than Scotland. The submarine landslide triggered at least one tsunami event that impacted the North Atlantic coast. In Scotland, the tsunami impacted around 600 km of coastline, extending several kilometres in land in places [2]. A recent reinterpretation of echosounder survey data of the Storegga slide [3] suggests that the Storegga slide includes two major submarine landslides: the Nyegga slide, which occurred at the end of the last Glacial Maximum around 20,000 years ago, as well as the Storegga slide, with the central section moving around 8150 ± 30 cal. yr BP [4] considered the main contributor to tsunami generation [5]. We follow the terminology suggested by [3,6] in referring to the later Holocene slide and tsunami as the Storegga slide and Storegga tsunami, respectively. Later events recorded in the Shetland Isles include the Garth tsunami and the Dury Voe event [6].

The Storegga tsunami deposits are probably the best mapped and most studied of palaeotsunamis [7]. As such, they have the potential to inform present day coastal man-

agement [7]. Deposits have been found in Norway [8–10], Scotland [2,11–13], the Shetland Islands [2,6], the Faroe Islands [14], and Greenland [15]. Studies of palaeotsunami deposits are an important aid in extending the long-term record and recurrence interval of high-magnitude events. Such information is used for risk management and to inform coastal communities so that they can prepare and plan for hazard mitigation [16–21]. In Scotland, Storegga tsunami deposits are exposed along the coast in the Shetland Isles [22], but outcrops on the Scottish mainland are rare. As a result, studies of tsunami sediments rely on auger borehole records and occasional trenches, e.g., [2]. Due to the lack of outcrops in Scotland and potential problems with borehole correlations [23], we used GPR to investigate the thickness and continuity of the Storegga tsunami sand layer. In addition, the depositional record of tsunamis can be incomplete due to non-deposition, erosion [24], and paedogenic alteration [25,26]. Furthermore, computer models still struggle to match observed run-up [22,27,28].

GPR has been used to image tsunami deposits in various places around the world, including Australia [29], the USA [30], Greece [31], Spain [32], Oman [33], Thailand [34], Sri Lanka [34], and Japan [35–37]. In addition, GPR has been used to investigate the Storegga slide tsunami deposits in the Shetland Islands [38,39]. Here, we report the results from the Scottish mainland where surveys were undertaken in areas with known tsunami deposits. The aims of the paper are to show the use of GPR to investigate the extent and geometry of tsunami sediments within an estuarine setting where the deposits are commonly covered by fine-grained estuarine ‘carse’ sediments. This contrasts with the Shetland Islands where the tsunami sands are interbedded with peat. Initial expectations were that the fine-grained sediments would attenuate the GPR signal, leading to relatively poor results. However, the results reported here exceeded our initial expectation, allowing us to map tsunami deposits in the shallow subsurface even when covered by younger marine sediments. We describe and discuss four sites on the east coast of Northern Scotland: Creich, Ardmore, and Dounie in the Dornoch Firth and Milton Farm on the River Wick; these locations can be seen in Figure 1.

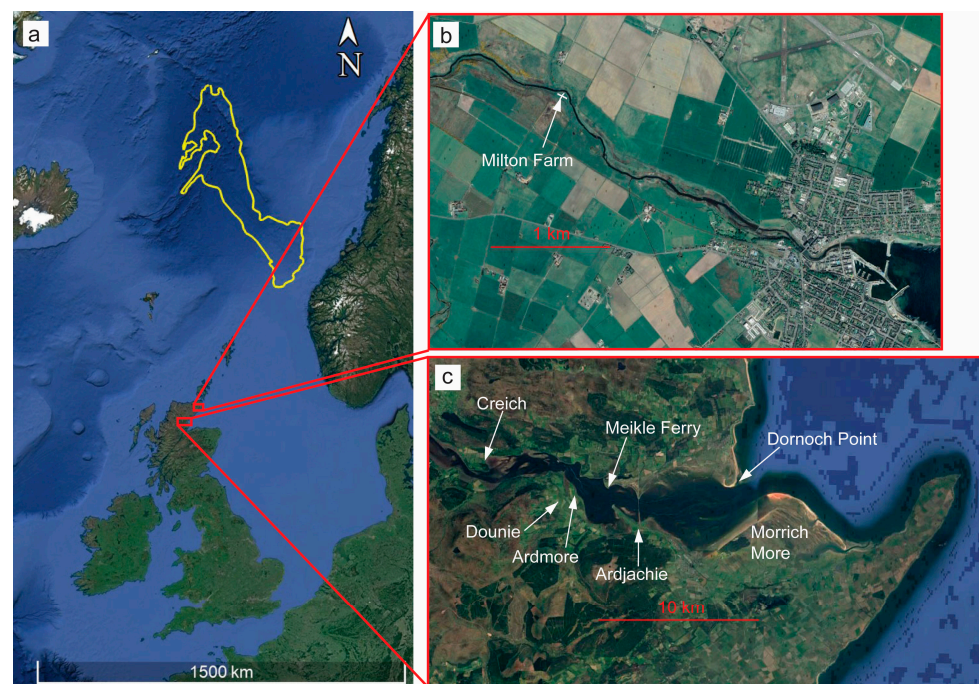


Figure 1. (a) Satellite image of UK and Ireland from Google Earth™. The outline of the Storegga slide shown by a yellow line, with red boxes showing (b) location of Milton Farm near Wick. (c) Creich, Ardmore, and Dounie around the Dornoch Firth. Detailed images of the survey sites at Milton Farm are shown in Figure 2, Creich is shown in Figure 3, Ardmore in Figure 4, and Dounie in Figure 5.

2. Study Areas

2.1. Milton Farm near Wick

The River Wick leads to a small SE–NW trending estuary on the northeast coast of Scotland. The site (coordinates $58^{\circ}27'9.87''\text{N}$, $3^{\circ}7'44.21''\text{W}$) is 2.6 km from the current coastline and lies in a field next to the River Wick. Storegga tsunami deposits at Milton Farm are documented by the authors of [11]. They illustrated the stratigraphy in three boreholes from this locality: their boreholes 20, 22, and 23 (Figure 2 in [11] p. 64). We collected two GPR profiles here: lines A–A', parallel to the river, along the line of the boreholes described by [11], and B–B', a perpendicular line that crosses line A–A' close to the location of their boreholes 22 and 21. Their locations are shown in Figure 2. Dawson and Smith [11] showed that, around the time of the Storegga tsunami (8150 ± 30 cal. years BP), sea level in this area would have been around 4 m lower than it is at the present day and demonstrated that the elevation of the grey, silty, fine-sand layer attributed to the tsunami rose inland by about 4 m over a distance of 760 m. Combining these two observations suggests a run-up of at least 8 m at Wick.



Figure 2. Satellite image showing location of GPR profiles and boreholes from [11], at Milton Farm near Wick.

The grey, silty, fine-sand layer described by [11] and attributed to the Storegga tsunami is around 0.05 m thick in boreholes 23 and 20, about 0.1 m thick in borehole 22, and enclosed within peat layers that appear to thin from 0.8 m in borehole 23 to about 0.25 m in borehole 20 to the east. The age of the thin sand layer in borehole 23 is constrained by radiocarbon dating of the enclosing peat, giving ages of 8104–7697 cal. yr BP above the sand and 8178–7844 cal. yr BP beneath the sand [2]. The basal peat is overlain by grey, sandy silt and silty fine sand with diatoms that indicate a transition from freshwater through brackish to marine conditions [11]. This unit thins to the west, from 1.65 m in borehole 20 to 0.45 m in borehole 23. In borehole 23, there are two thin peat horizons dated at 4400 ± 50 and 1130 ± 50 radiocarbon years BP. These peat layers are not recorded in boreholes 22 and 20. Above the thin peat horizons, there is a change in lithology to grey, organic, silty clay that is correlated across the three boreholes and contains diatoms that indicate a gradual change from freshwater to brackish conditions in borehole 23 [11]. At the top of each borehole is a mottled brown-grey, silty clay with rootlets that is part of the active freshwater floodplain of the River Wick.

2.2. Creich

Creich is an embayment on the north side of the Dornoch Firth (coordinates $57^{\circ}52'3.08''\text{N}$, $4^{\circ}17'10.32''\text{W}$), which is a W–E trending inlet off the western edge of the Moray Firth in Scotland. Two raised marine terraces in the embayment, with elevations of 5.3 to 6.0 m OD and 3.9 to 4.7 m OD (Ordnance Datum) and with a reconstruction showing spits across the entrance to the embayment, attached to both the north and south sides with a narrow entrance in the middle of the embayment, are shown by [40]. Boreholes taken by the authors of [40] show that the two raised marine terraces are underlain by a light-grey clay; peat; grey sand; grey, silty, fine sand; and gravel. Based upon limited borehole data, ref. [40] shows the sand layer as laterally continuous and thinning gently towards the sea in this area. An additional auger hole was made in this field, but material was left in the field overnight and was eaten by cows. As a result, data from this field were limited, but a stratigraphic section based on borehole data suggests that the sand layer extends across the embayment, thickening and thinning inland, with a maximum thickness of 1.6 m and a maximum elevation of 7.1 m OD [40]. Diatoms within the grey sand indicate a marine environment, and the sand layer was interpreted as a marine transgression [40], although the sand layer was later interpreted as a tsunami deposit associated with the Storegga slide [41]. Radiocarbon ages of peat above and beneath the sand layer are 7572–7341 cal. yr BP and 7935–7677 cal. yr BP, respectively [2]. These ages are slightly younger than the age of 8150 ± 30 cal. yr BP that is accepted for the Storegga slide tsunami [4], possibly due to contamination by younger carbon, but the sand layer is interpreted as a tsunami deposit caused by the Storegga tsunami [2]. Nineteen GPR profiles, totalling 3866 m, were collected here to map the thickness of the sand layer, which is unusually thick for a tsunami deposit. The GPR profiles form a loose grid, and eight auger boreholes were also taken, the locations of which are shown in Figure 3.

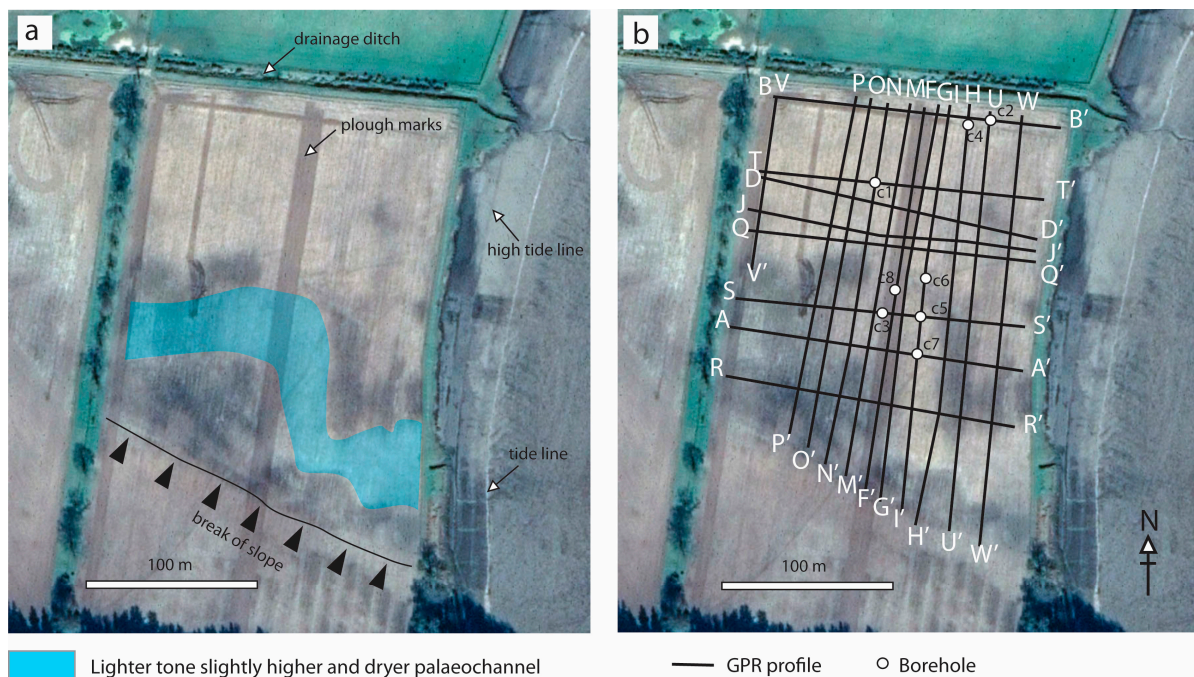


Figure 3. Satellite image of the study area at Creich. (a) In this image from April 2019, the field has been cultivated with no crops growing. Darker areas are wet soil; pale-coloured areas are dryer and a little bit higher. The pale-blue area is interpreted as a palaeochannel. A break of slope is marked where Holocene sediments abut Pleistocene sediments. (b) Location of GPR profiles and boreholes at Creich, the GPR lines are identified by letters A–W and the boreholes are identified by numbers c1–c8. Google Earth image CNES/Airbus.

2.3. Ardmore

Ardmore lies on the south side of the Dornoch Firth on a promontory that projects into the firth (coordinates $57^{\circ}50'58.35''\text{N}$, $04^{\circ}10'42.06''\text{W}$) (Figure 4). Geomorphological mapping at Ardmore by the authors of [40] shows two raised shingle beach ridges parallel to the shore that are connected to a terrace in the south. A sketch cross-section at Ardmore is shown in [42]. This shows three shingle ridges with the two eastern, seaward ridges standing higher (8.5 and 8.4 m O.D.) than the third, which is lower lying (7.2 m O.D.). The tsunami is believed to have overtopped the third ridge, depositing a sand layer on the landward side [42]. Two GPR profiles perpendicular to the beach ridges were collected here to investigate the relationships between the shingle ridges and the tsunami sand layer, the locations of which are shown in Figure 4. The two GPR profiles, A-A' and B-B', are separated by a field boundary with a low embankment and a fence.



Figure 4. Satellite image showing location of GPR profiles, red lines A-A' and B-B', at Ardmore.

2.4. Dounie

Dounie is located to the west of Ardmore and is roughly 1.5 km further inland (coordinates $57^{\circ}48'4.97''\text{N}$, $4^{\circ}14'57.83''\text{W}$). A cross-section based on boreholes taken by the authors of [40] shows peat deposits with an interbedded sand layer that is interpreted as a tsunami deposit pinching out inland and rising to an elevation of 7 m. Radiocarbon dating of the peat immediately above and below the sand layer after calibration shows the radiocarbon ages are 8104–7793 and 6170–5750, respectively [2], close to the accepted age for the Storegga tsunami of around 8150 years BP [4]. At Dounie, the sand layer is very extensive, extending over 1.5 km inland and up to 1.39 m thickness in boreholes [43]. Four GPR profiles were taken here to investigate the extent and continuity of the sand layer and explore the resolution of the sand layer at its inland limits. The locations of the GPR profiles are shown in Figure 5. The profile Dounie A-A' and B-B' is oriented SW–NE; it is

435 m long and crosses two fields separated by a fence. In the first field, the vegetation was very thick with tussocks of sedges, resulting in inconsistent ground contact along line A-A'. The second field was close-cropped pasture, giving better ground contact. This area has been drained for agriculture, with a deep drainage ditch along the northern field boundary and land drains across the field. In 2022, two perpendicular GPR profiles were collected in a grass field on the east side of the A 836 (Figure 5). Dounie C-C' is W-E and Dounie D-D' is S-N to investigate the area between Dounie and Ardmore. This is a pasture field with no distinct geomorphological features on the ground or on the satellite image (Figure 5).



Figure 5. Satellite image showing location of GPR profiles, red lines A-A', B-B', C-C' and D-D', and auger borehole D1 at Dounie.

2.5. Methods

For the GPR surveys, a PulseEKKO Ultra with 100 and 200 MHz antennas was used. The 100 MHz antennas were spaced 1 m apart with a step size of 0.25 m; the 200 MHz antennas were spaced 0.5 m apart with a step size of 0.2 m. Topographic elevations along the profiles were measured at 5 m intervals using a Leica NA320 level. For depth estimates and static elevation corrections, a velocity of 0.06 m/ns was used for the profiles at Wick, Creich, and Dounie. At Ardmore, a velocity of 0.12 m/ns was applied because the beach ridges are composed of coarse pebbles and cobbles that are well drained. These velocities were calculated from CMP surveys at each site. Using these velocities and the 100 MHz antenna frequency, the wavelength of the GPR signal was calculated to be 0.6 m. Assuming a resolution of one-fourth of the wavelength gave a theoretical depth resolution of 0.15 m at Milton Farm near Wick, Creich, and Dounie. The GPR data and topographic surveys were conducted in May 2019 at Wick and Creich, with additional data collected at Creich, Dounie, and Ardmore in August 2019, July 2020, and April 2022. Subsequent data processing was performed using Sensors and Software EKKO Project 5 software. The processing steps at each site included SEC gain and topographic correction; in addition, FK migration was applied to the profile at Ardmore to restore dipping reflections. This was not applied to the other profiles because the dips are generally very low and hyperbolic reflections are useful to check velocity calculations and indicate the presence of buried objects and drainage pipes. GPR interpretation uses a combination of radar facies analysis and radar stratigraphy, following [44,45]. At Creich, surface elevation graphs were created for the top of the sand layer and its base. The elevation of the base was subtracted from the elevation

of the top to give the thickness of the sand layer. Plotly, an online tool that uses python to create 3D graphs, was used to visualise the results.

3. Results

After initial tests to compare the depth of penetration and resolution of the 100 and 200 MHz antennas, the 200 MHz antennas were used for the surveys at all locations. Based on reflection characteristics, six radar facies were defined following the method of [46], combined with radar stratigraphy [44,45]. The radar facies are shown in Table 1 and Figures 6, 7, 10, and 11. Lithological descriptions of sediments in boreholes are based on a visual assessment of the sediment grain size (Figure 8). The term clay refers to clay-sized particles rather than clay minerals unless explicitly stated.

Table 1. Radar facies descriptions and interpretations for Holocene sedimentary environments encountered on the northeast coast of Scotland.

Radar Facies	Description of Reflection Characteristics	Colour	Interpretation of Depositional Environment
RF1	Continuous, sub-horizontal, high-amplitude reflections, thickens and thins laterally.	Pink	Tsunami sand layer
RF2	Continuous, sub-horizontal, low-amplitude reflections, with broad concave reflections.	Brown	Back-barrier/estuarine intertidal sediments and freshwater marsh
RF3	Inclined tangential reflections that dip towards the sea.	Yellow	Beach deposits
RF4	Inclined tangential reflections that dip towards the land.	Purple	Washover deposits
RF5	Packages of short, inclined reflections bounded by low-angle convex and low-amplitude concave reflections that truncate other low-angle reflections.	Blue	Tidal channel deposits
RF6	Packages of inclined, planar, and sigmoid reflections with concave or irregular erosional surfaces at base.	Orange	Lateral accretion in fluvial channel
RF7	Discontinuous hyperbolic reflections, high-attenuation, locally reflection-free. Migration produces artifacts with short concave reflections.	Green	Fluvioglacial terrace deposits

3.1. Milton Farm

3.1.1. Description

At Milton Farm, two GPR profiles were collected, Milton Farm A-A' and Milton Farm B-B'. The results for these can be seen in Figure 6. Milton Farm A-A' is oriented in a NW–SE direction, with the 90 m end towards the sea, and is roughly parallel to the river, running between boreholes 23, 22, and 20 of [11]. The line starts at borehole 23 and ends at borehole 20, crossing borehole 22 at 44 m. Milton Farm B-B' is a 50 m profile line perpendicular to Milton Farm A-A' and crossing at borehole 22, which is 26 m along Milton Farm B, oriented in a SW–NE direction with the 50 m side towards the river (Figure 6d).

At first glance, the GPR profile A-A' showed continuous sub-horizontal reflections at shallow depths (1–2 m elevation), but on closer inspection, it was apparent that the reflections were not continuous and showed truncations where one reflection terminates against another (Figure 6a,b). Truncations can be seen between 20 and 30 m, 40 and 50 m, and 60 and 70 m on profile A-A'. These shallow reflections are coloured red, yellow, and orange to aid their identification in Figure 6b. The deeper reflection forms a continuous sub-horizontal reflection between 25 and 90 m, but at 25 m, it divides, forming two reflections that define a triangle, shaded orange in Figure 6b. On profile B-B', the shallow reflections are continuous and gently inclined, while the deepest reflection dips from SW to NE between 50 and 40 m, flattens out between 40 and 35 m, and then rises between 35 and 30 m (Figure 6d).

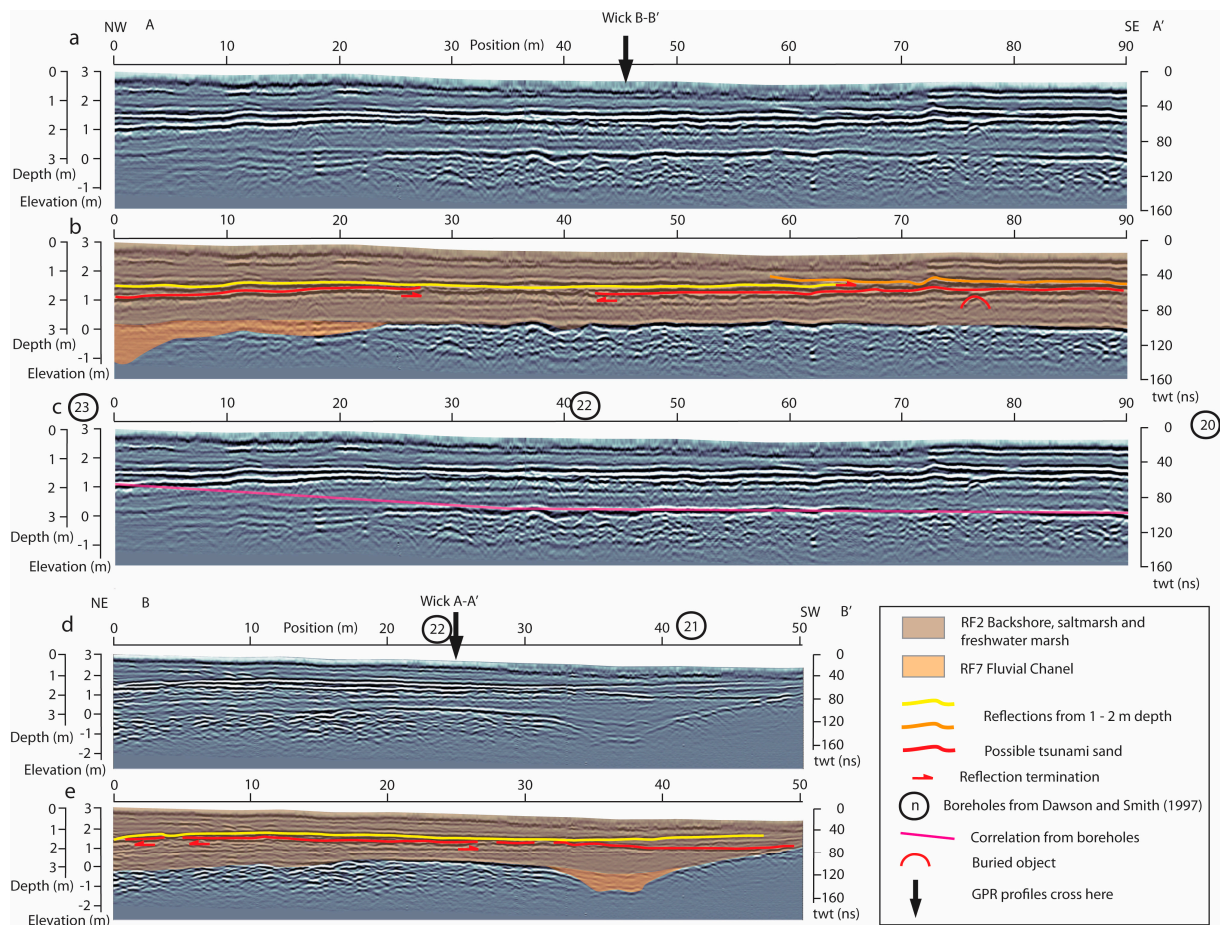


Figure 6. GPR data from Milton Farm near Wick. (a) GPR profile A-A' between boreholes 23 and 20 of [11]. (b) Reflections at depths of 1 to 2 m are coloured red, yellow, and orange and are not continuous across the whole profile. The red reflection is correlated with a tsunami sand identified by [11] in borehole 23 and is truncated by the yellow reflection between 30 and 40 m, interpreted as local erosion of the sand layer. The yellow reflection is truncated by the orange reflection. As a result, the sand layer in borehole 23 is not present in borehole 20. (c) The pink line indicates correlation of sand layers made by [11]. The pink line does not follow the stratigraphy shown by GPR, showing that there is a miscorrelation. (d) GPR profile B-B' is perpendicular to A-A' and the surface slopes gently from NE to SW away from the River Wick due to a levee. (e) The base of the section is interpreted as a fluvial erosion surface (orange fill (RF7)) from a precursor to the River Wick. The reflection interpreted as the tsunami sand (red) is truncated by a younger erosion surface (yellow).

3.1.2. Interpretation

The deepest reflection on A-A' and B-B' is interpreted to be a river channel that was a precursor to the modern River Wick. This reflection is the lowest in the stratigraphy and therefore the oldest feature seen. The palaeochannel is shown in orange in Figure 6b,e. The profile A-A' that runs along the valley is sub-parallel to the channel and the cross-section is incomplete, showing just a triangular section. On profile B-B', which runs across the valley, a channel cross-section can be seen (orange area (RF7)) between 30 and 40 m (Figure 6e). The shallow reflections between 1 and 2 m depth are correlated with the strata in borehole 23 of [11]. In borehole 23, [11] identifies the tsunami sand at a depth of 2.3 m. The sand layer is enclosed by peat that has been radiocarbon dated. The closest reflection to 2.3 m at the northwest end of profile A-A' is the reflection coloured red in Figure 6b. Tracing the red reflection on profile A-A', it is truncated by the overlying yellow reflection between 30 and 40 m. These reflection terminations, marked by red half arrows, indicate where the underlying layer of strata has been eroded. In this case, it shows that the red reflection

interpreted as the tsunami sand layer has been locally eroded. The yellow reflection is truncated, eroded by the orange reflection. As a result, the stratigraphy at the north end of profile A-A', as shown in borehole 23, is not the same as the strata at the SW end, in borehole 20 of [11], or in the middle, near borehole 22 where the tsunami sand layer (red reflection) has been eroded. The tsunami sand layer at a depth of 2.3 m in borehole 23 was correlated by [11] with a sand layer within an undated peat at a depth of 2.4–2.5 m in borehole 22 and around 2.3 m in borehole 20. This correlation is depicted by the pink line in Figure 6c. The pink line joins different reflections, showing that the layers that were correlated by [11] are not the same and that there was a correlation error largely attributed to erosion of the shallow sediments on the river floodplain.

3.2. Creich

3.2.1. Description

At Creich, there are 11 N–S GPR profiles parallel to the coast and 7 W–E profiles perpendicular to the coast. Here, we illustrate two examples: line B (Figure 7) is an example of a W–E profile, and line G (Figure 7) is an example of a N–S profile. On each GPR profile, there are two or three continuous reflections that undulate. The amplitude and polarity of the reflections vary, and, in places, the reflections are cut, truncated by concave discontinuous reflections with a low-amplitude fill (RF2), e.g., around 80 m and 130 m on profile G (Figure 7a,b). Changes in the reflection character are interpreted as different radar facies. Radar facies 1 is usually continuous, with undulating sub-horizontal, high-amplitude reflections that thicken and thin laterally. RF1 is commonly truncated by concave low-amplitude reflections of RF5. A small area of inclined reflections is found at 120 m on profile B (Figure 7c,d). Mapping the top sand surface appears to show a low-amplitude ridge heading inland with distinct ridges and troughs parallel to the shoreline (Figure 8). The base of the sand layer (Figure 8) also shows a central ridge and transverse ridges and troughs. The resulting sand thickness map is dominated by north–south trending ridges and hollows with wavelengths of around 50 m and amplitudes of around 2 m that are roughly parallel to the coast. The GPR profiles perpendicular to the coast, including profile B (Figure 7), show that the base of the sand layer undulates, and this accounts for much of the observed sand thickness (Figure 8). It is unclear if these observed thickness changes are due to the sand burying a pre-existing topography or shore parallel erosional structures created by the tsunami, but burial of a pre-existing topography and differential compaction over older channel sands seems more likely.

3.2.2. Interpretation

Line B (Figure 7c,d) shows reflections that are continuous but undulate across the western half of the profile, while reflections intercept the surface and show truncations towards the sea in the east. A reflection-free package bounded above and beneath by relatively high-amplitude continuous reflections (RF1) is interpreted as the tsunami sand layer and coloured pink.

Line G (Figure 7a,b) shows continuous reflections with a greater number of truncations. The tsunami sand layer shown in pink (RF1) has a maximum thickness of 1 m, but the thickness changes along the profile, with gaps between 85 and 120 m and 130 and 140 m, where the sand layer has been eroded by younger tidal channels (RF5). The tsunami sand layer (RF1) is commonly underlain and overlain by low-amplitude packages of sub-horizontal reflections (RF2) interpreted as intertidal saltmarsh or mudflat sediments. The inclined reflections at 120 m on profile B are interpreted as beach and washover deposits (RF4 and RF3). This interpretation is supported by the geomorphological mapping of [40] and the borehole results described below. RF5, blue-coloured, low-amplitude, concave reflections, are interpreted as tidal channel deposits. The low amplitude of the basal reflections is attributed to minor lithological changes between the tidal channel fills (RF5) and the associated fine-grained backshore sediments (RF2). The tidal channel fills (RF5) often appear as slightly elevated areas on the profile because, after drainage and compaction,

the tidal channel facies have compacted slightly less than the fine-grained marsh sediments, RF2. Differential compaction and inverted topography appear beneath the sand layer at 115 m on line G (Figure 7).

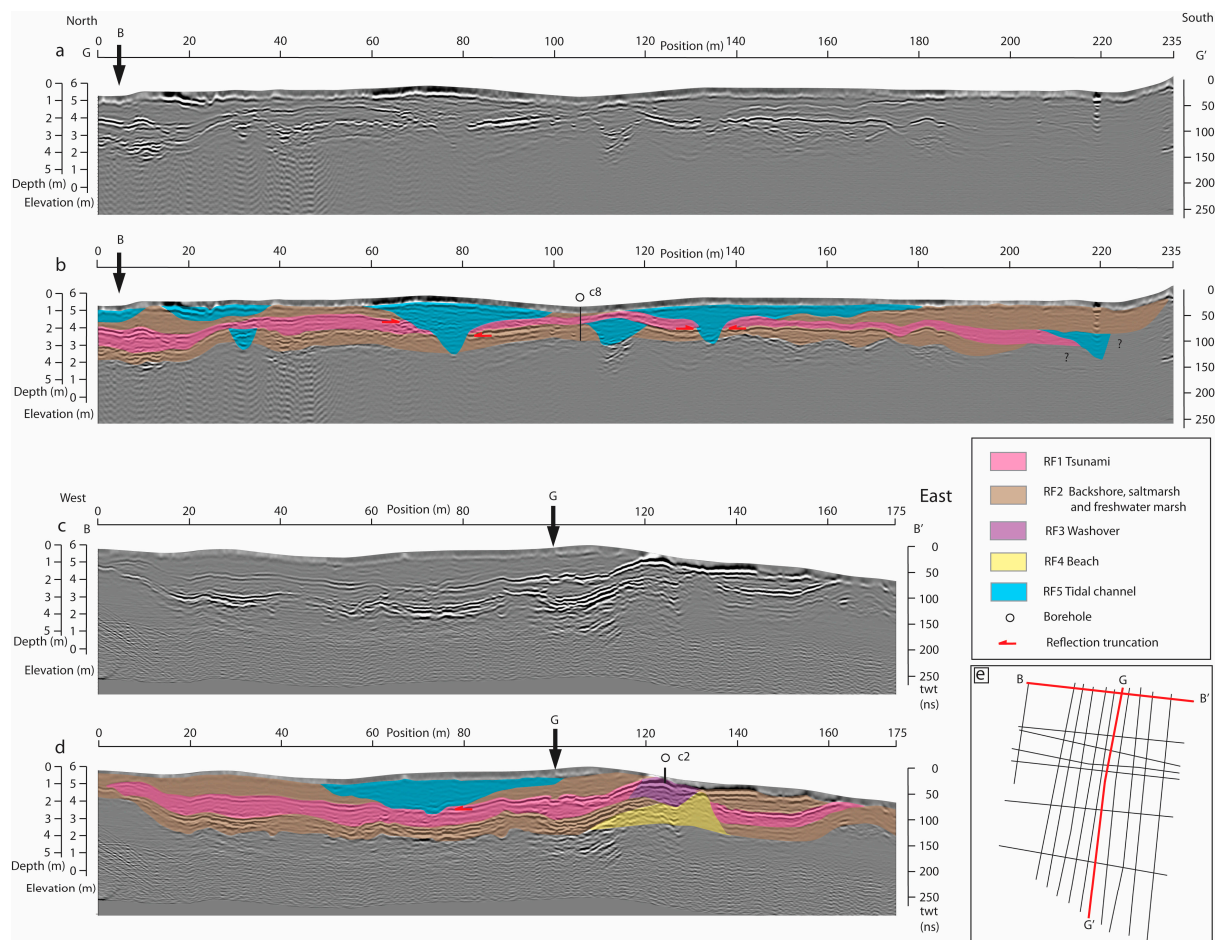


Figure 7. GPR data for Creich lines G-G' (a,b) and B-B' (c,d). The tsunami sand (RF1, pink) is sandwiched between low-amplitude packages of RF2 (brown) and RF5 (blue), interpreted as marsh and tidal channels, respectively. The blue tidal channel facies locally cut into the pink tsunami reflection. This erosion explains some of the thickness changes observed in Figure 8, but the base of the tsunami layer also changes elevation, indicating a buried topography. Inset (e) shows the a plan of the GPR profiles with lines B-B' and G-G' in red.

Mapping the top sand surface shows shore parallel trends with distinct ridges (yellow) and troughs (red) parallel to the shoreline (Figure 8). The base of the sand layer also shows transverse ridges and troughs that follow a similar trend. The resulting sand thickness map is dominated by north–south trending ridges and hollows with wavelengths of around 50 m and amplitudes of around 2 m that are roughly parallel to the coast. The GPR profiles perpendicular to the coast, including profile B (Figure 7), show that the base of the sand layer undulates, and this accounts for much of the observed sand thickness (Figure 7). It appears that most of the elevation changes can be attributed to differential compaction related to the underlying intertidal channels, where the channel deposits have compacted less than the adjacent mudflats and supratidal marsh sediments. On top of that, later erosion by tidal channels has locally eroded the tsunami sand layer, resulting in a complex pattern of thickness changes in 3-D (Figure 8).

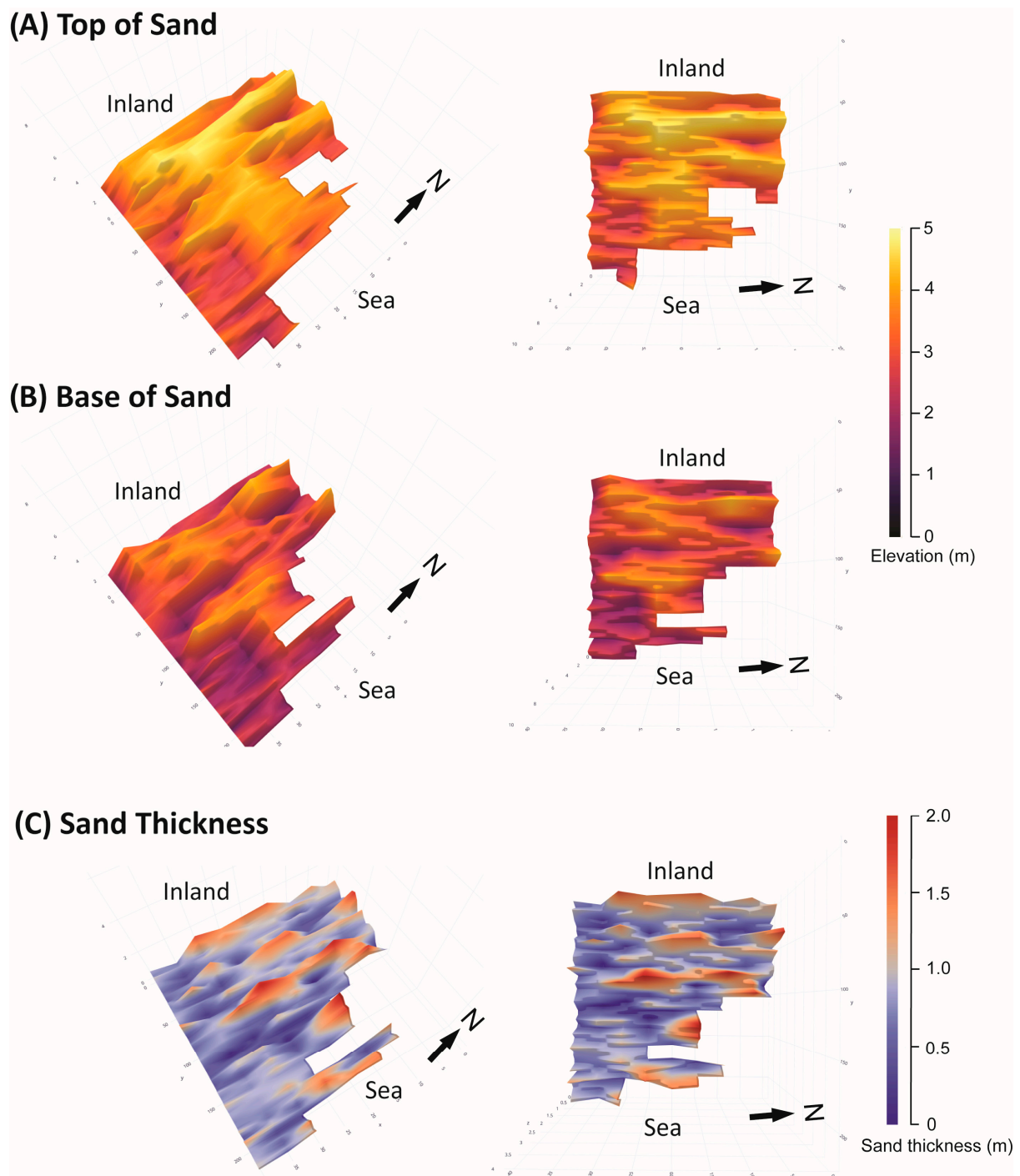


Figure 8. (A) Surface graph showing the elevation of the top of the sand layer. (B) The elevation of the base of the sand layer with the black-to-yellow scale bar from 0–5 m elevation. (C) The thickness of the sand layer derived by subtracting the base elevation from the top elevation, with the blue-to-red scale bar from 0–2 m. The thickness changes are attributed to differential compaction over intertidal channel and mudflat and supratidal marsh sediments with later erosion adding to the complex 3-D changes in thickness.

Auger borehole data show that the top of the sand was encountered at a depth of 1.2 m in borehole C1, at 1.34 m in C3, 0.8 m in C4, 0.5 m in C5, 1.08 m in C6, 1.4 m in C7, and 0.95 m in C8 (Figure 9). The base of the sand was not encountered in borehole C1, which terminated at 2.15 m, or C7, which terminated at 1.66 m. There was no sand in C2, and the base of the sand was encountered at 2.24 m in C3, 2.0 m in C4, 0.7 m in C5, 1.4 m in C6,

and 1.35 m in C8. Boreholes C1, C3, C4, C5, C6, and C7 show sand layers of greater than 0.95 m, 0.9 m, 1.2 m, 0.2 m, 0.32 m, 0.26 m, and 0.4 m, respectively. The sand layer in the boreholes corresponded to the package of GPR reflections identified in the GPR profiles in pink in Figure 7. C2 repeatedly struck rock. Its location falls on line B at 125 m, where the purple RF3, interpreted as washover deposits, reaches the surface, confirming the presence of coarse gravels. Freshwater reeds were found in the material below the sand layer in C3, C4, and C6. The material above and below the sand was silt or clay, with the very top layer being loam.

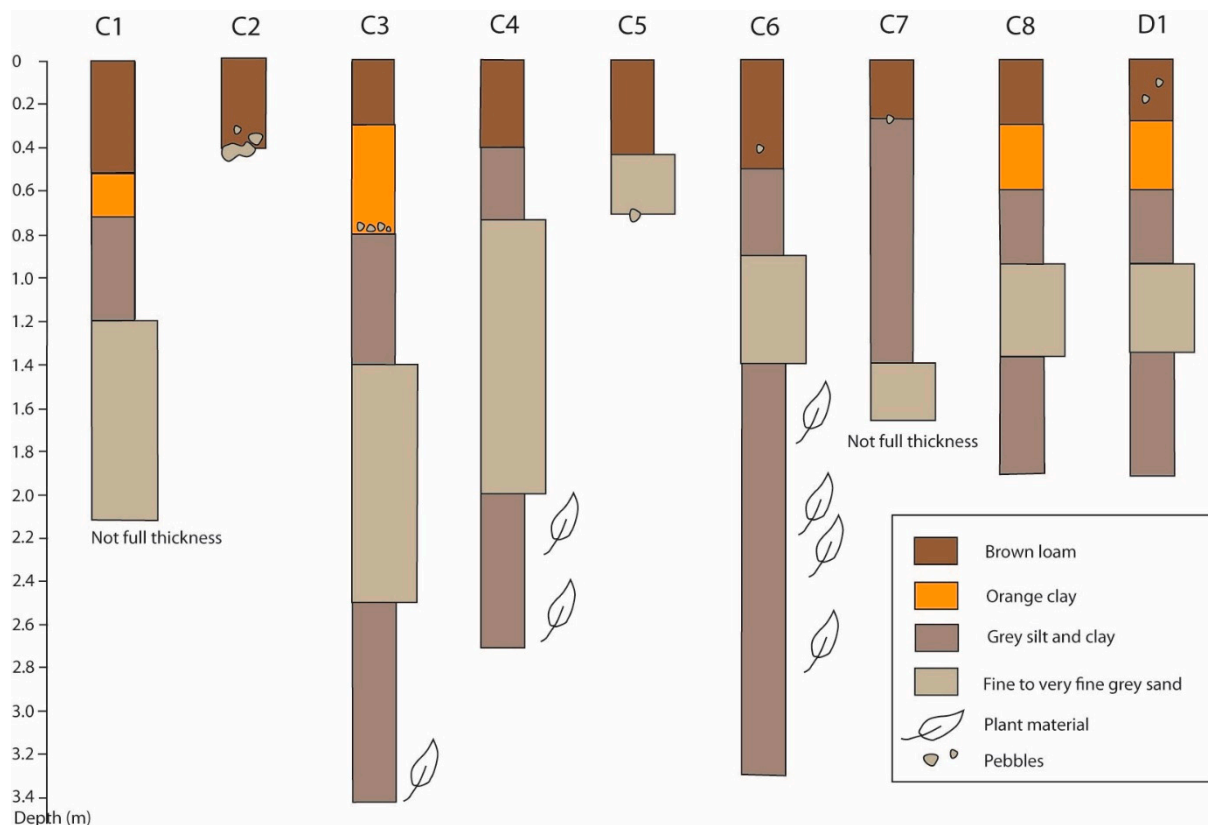


Figure 9. Summary lithology logs for auger boreholes at Creich and Dounie.

3.3. Ardmore

3.3.1. Description

The GPR profile at Ardmore was collected in two parts either side of a fence and low embankment that is a field boundary dividing the two higher elevation beach ridges in the east from the lower ridge in the west. On the eastern, seaward side of the fence, from 0–93 m, the GPR profile shows many inclined reflections that dip towards the sea (RF4), downlapping onto low-angle reflections of RF5, with an undulating reflection at the base (Figure 10). Between 70 and 93 m, the reflection pattern changes with reflections dipping inland, towards the west, including landward dipping reflections (RF3) and low-angle reflections of RF2.

On the landward side of the fence, at 100–275 m, the GPR profile shows more low-angle reflections of RF2 at both ends with landward inclined reflections of RF3 in the middle and a small package of seaward dipping reflections (RF4) between 160 and 170 m (Figure 10). The tops of the inclined reflections RF3 and RF4 are marked by a continuous high-amplitude reflection, coloured red in Figure 10, that can be traced seaward beneath RF2 and landward as well.

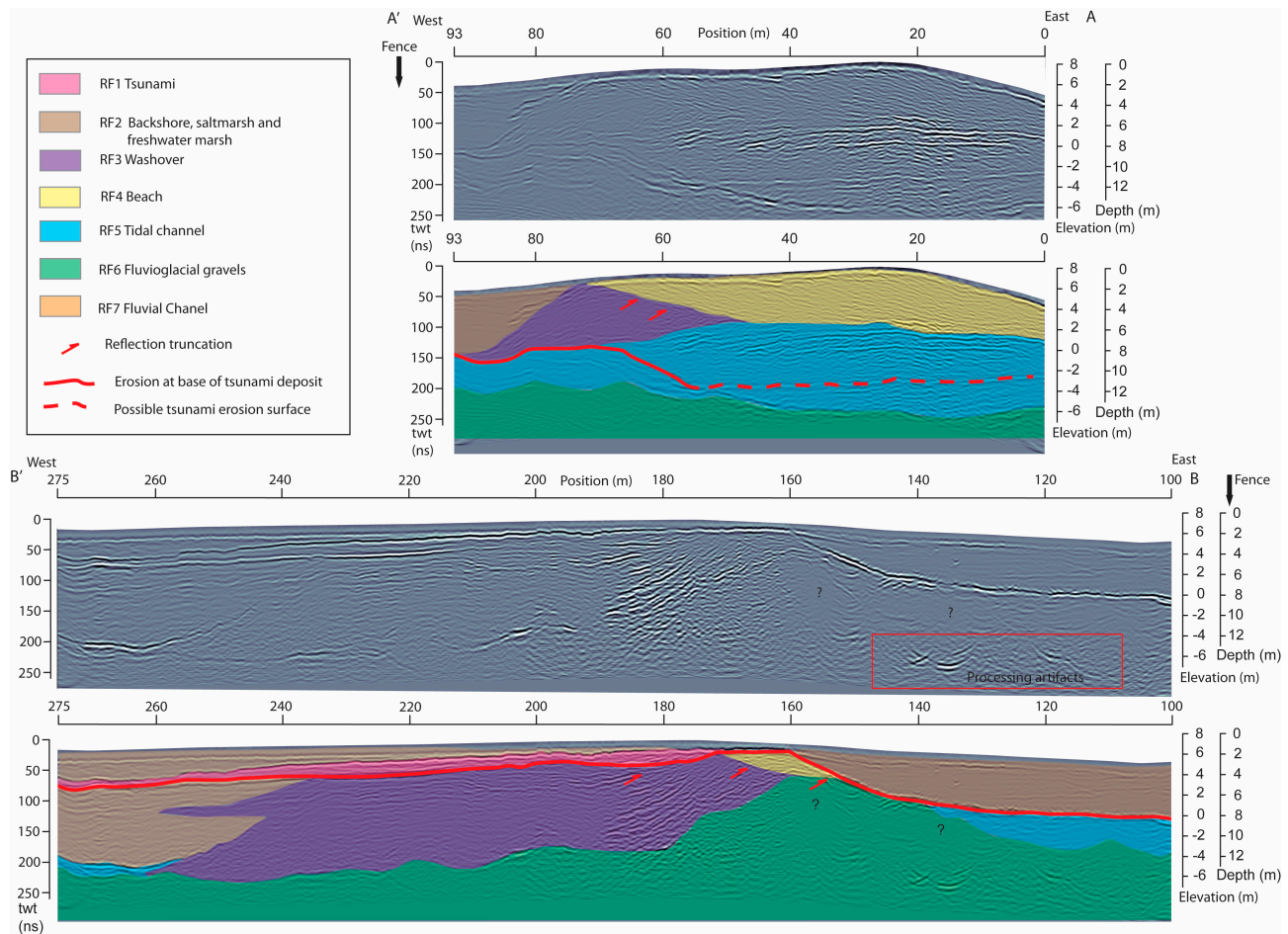


Figure 10. GPR data from Ardmore with the A close to the sea, and B' at the inland end (see locations on Figure 4). The tsunami erosion surface (red line) appears to have washed over and truncated an earlier beach ridge between 160 and 240 m that is dominated by landward dipping washover deposits (RF3). The beach ridges closer to the sea are younger and contain more prograding beach deposits (RF4).

3.3.2. Interpretation

The GPR data from Ardmore are coloured by radar facies (Figure 10). Radar facies 4 (yellow) is interpreted as beach deposits formed on the seaward side of the shingle beach ridges; the downlap relationship indicates progradation as the spit built out over tidal channel deposits (RF5, blue). Radar facies 3 (purple) is interpreted as washover deposits deposited on the landward side of the shingle beach ridges. The underlying reflection at the base of RF5, top of RF6, is interpreted as an erosion surface overlying fluvioglacial outwash, which forms the terrace to the south of the spits. Towards the base of the GPR profile, there are discontinuous low-amplitude reflections, many of which have become concave 'smiles', labelled 'processing artifact', between 150 and 110 m in Figure 10. The concave 'smile' reflections result from over-migration, that is, migration with an incorrect velocity, e.g., [47,48]. In this case, the velocity of 0.12 mns^{-1} was used for the elevation correction on the well-drained shingle spits, while a velocity of 0.06 mns^{-1} should be applied to saturated sand and gravel beneath the water table, which is close to sea level. Radar facies 2 (brown) is interpreted as fine-grained intertidal sands and silts deposited in a sheltered backshore environment between or to landward of the shingle ridges. The continuous high-amplitude reflection, coloured red in Figure 9, is interpreted as an erosion surface, most likely formed during the tsunami. The tsunami erosion surface appears to truncate inclined reflections of RF3 and RF4, indicating erosion of the third beach ridge during the tsunami. On the landward side of the third ridge, another high-amplitude sub-horizontal

reflection is visible; the wedge of sediment between these two reflections is interpreted as the tsunami overwash (RF1 pink). Tracing the red-coloured, high-amplitude reflection to seaward, it passes beneath RF3 and RF4, showing that the two outer ridges of the spit formed after the tsunami, most likely during the mid-Holocene sea-level highstand, which supports the interpretation of [42]. Between 60 m and 0 m, the probable tsunami erosion surface is indicated by a dashed line because it is unclear which reflection should be picked (Figure 10). It is notable that the older, lower elevation spit west of the fence appears to be built upon the eroded remains of fluvioglacial outwash (RF6, green) and dominated by washover (RF3), while the younger spits are dominated by beach progrades (RF4). This change in depositional pattern from washover dominated to progradational is attributed to a change in the contemporary sea-level trends, with the older spit showing a regressive overwash stratigraphy during the early Holocene transgression while the later spits have a progradational trend during the mid-Holocene highstand.

3.4. Dounie

3.4.1. Description

The GPR profile Dounie A-A' and B-B' runs across a shallow valley floor and is in two parts, divided by a fence line that separates two fields. The GPR profile is dominated by continuous sub-horizontal reflections that can be correlated most of the way across the valley, some of which pinch out towards the valley margins. The outstanding exception is a concave package of discontinuous reflections between 280 and 300 m, shown in orange (RF6) (Figure 11). The reflections that pinch out towards the valley margin define a package of low-amplitude reflections that are coloured pink (RF1). A small, V-shaped reflection, shown in orange (RF6), can be seen centred at 220 m. The GPR profile Dounie C-C' shows a distinct change in reflection character between the western and eastern halves (Figure 11). The eastern half, 0–50 m, shows discontinuous inclined reflections (RF6). From 50 to 100 m, this package becomes more organised and shows a wide shallow trough overlying a thinner package of discontinuous reflections with an undulating base (Figure 12). Between 100 and 150 m, the reflections are continuous and sub-horizontal (RF1 and RF2), with a package of discontinuous inclined reflections near the surface between 120 and 150 m (Figure 12). GPR profile Dounie D-D' that is perpendicular to Dounie C-C' shows a similar change in reflection pattern, with discontinuous inclined reflections dipping towards the north between 0 and 50 m (RF6) (Figure 11).

3.4.2. Interpretation

The distinct concave package of discontinuous reflections between 280 and 300 m on GPR profile Dounie B-B' (Figure 11) is interpreted as a fluvial channel fill (RF6). This is likely to mark the position of a small river or burn that flowed along the valley before the fields were drained for cultivation. The continuous horizontal reflections that can be seen wedging out towards the valley margin (RF1) can be correlated with a layer of grey sand, described in boreholes [40] and interpreted as a tsunami deposit [49]. High-amplitude continuous reflections at the SW end of profile A-A' are correlated with layers of peat, shown in the boreholes of [40] (their Figure 5C of [40]).

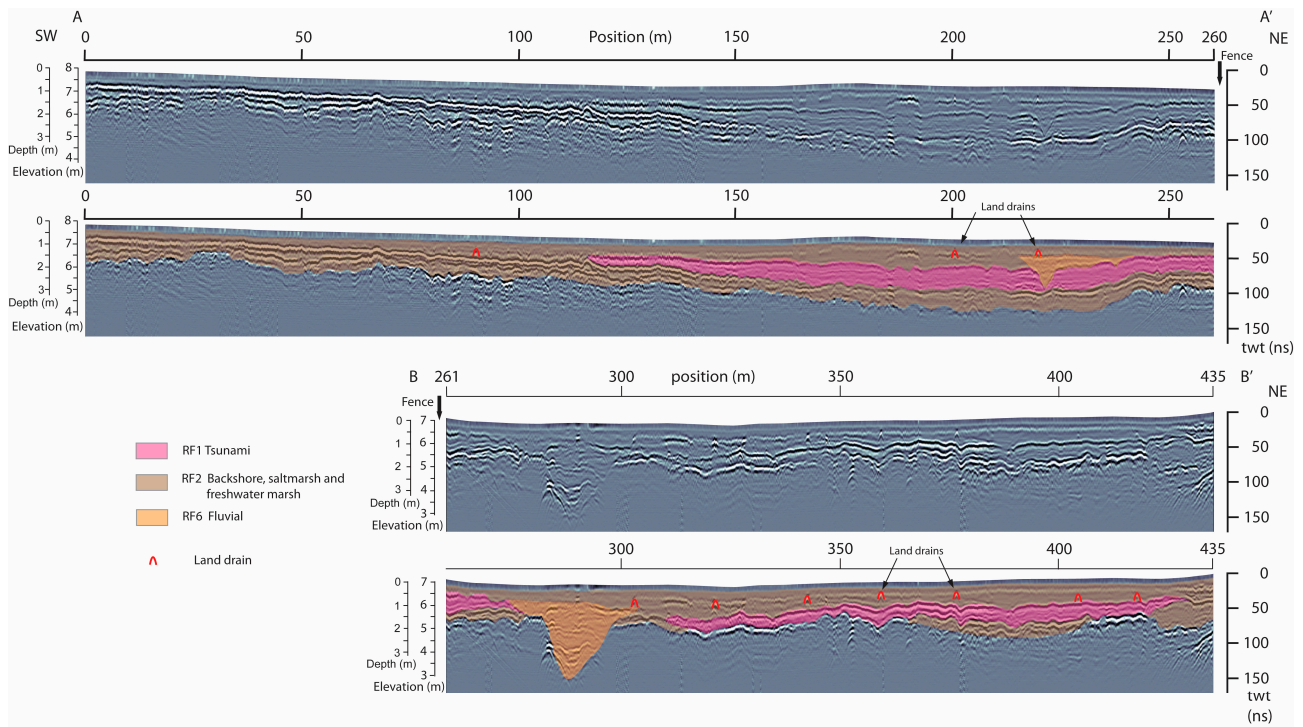


Figure 11. GPR profile A-A' and B-B' across a shallow valley at Dounie. The tsunami sand layer (RF1) thickens into the middle of the valley and pinches out against the valley margins. It is cut by a fluvial channel between 280 and 300 m.

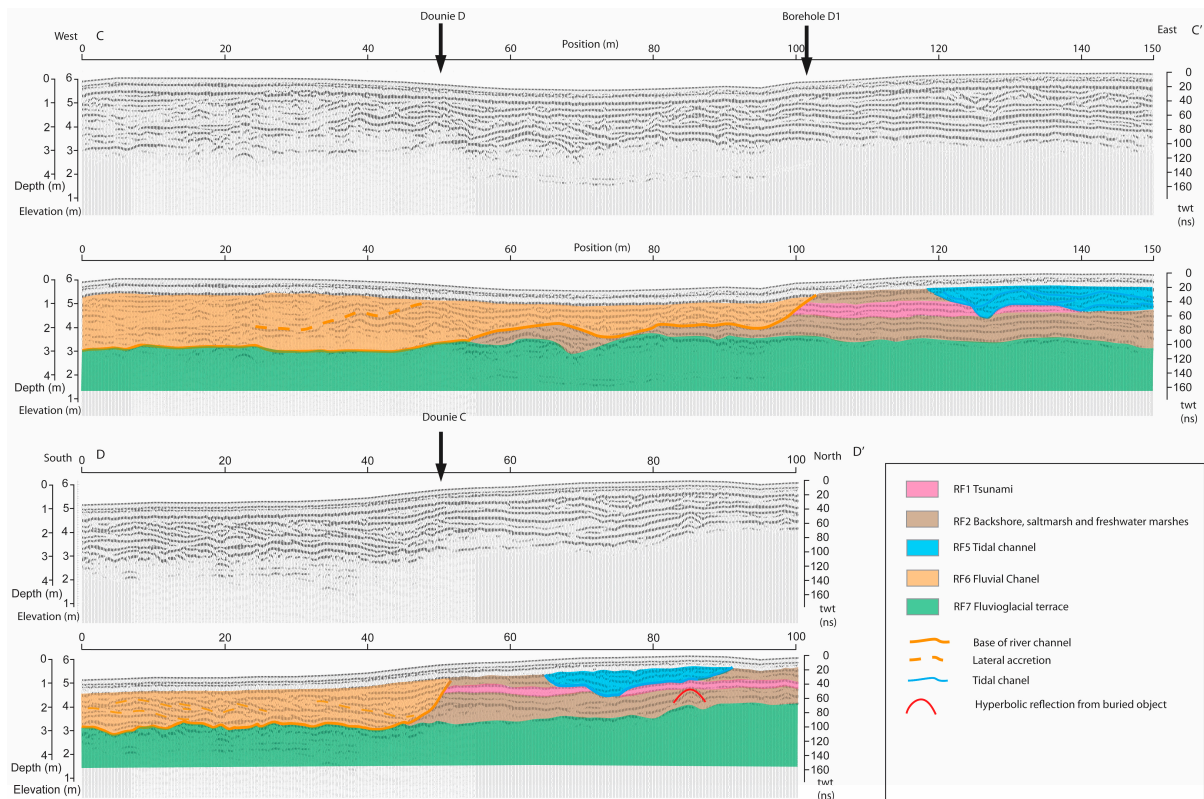


Figure 12. GPR profiles Dounie C-C' and D-D' are perpendicular to each other and show river deposits (RF6) in the south and west, cutting into tsunami and tidal flat sediments, RF1 and RF2, in the north and west.

GPR profiles Dounie C-C' and D-D' show distinct differences in reflection character that were interpreted as different depositional environments. Continuous horizontal reflections at the eastern end of profile C-C' and the northern end of D-D' are interpreted as the tsunami sand layer (RF1), sandwiched between fine-grained, back-barrier estuarine and marsh deposits (RF2) (Figure 12). A single borehole at D1, located 105 m along line C-C', recorded 0.85 m of sand at depths between 0.75 and 1.6 m (Figure 9), which is consistent with borehole records of the sand layer reported by [40,49]. The continuous sub-horizontal reflections of RF1 and RF2 are truncated by an erosion surface at 100 m on C-C' and 50 m on D-D' that is interpreted as the cutbank on the outside of the river bend, which can be traced laterally beneath the river deposits (RF6) (Figure 12). The northward dipping, inclined reflections between 0 and 50 m on GPR profile D-D' are interpreted as lateral accretion surfaces from deposition on the convex side of a river meander bend. The erosional cutbank on the outside of the bend is close to the intersection with profile C-C'. While profile D-D' shows sigmoidal pointbar geometry, the perpendicular profile C-C' shows channel geometry with a slight depression underlain by a broad trough-shaped reflection between 50 and 100 m that likely represents the channel abandonment before the area was drained for agriculture.

4. Discussion

In the Shetland Islands, Storegga tsunami sand beds are interbedded with peat, and this combination of lithologies produced good reflections on GPR profiles [39]. On the Scottish mainland, the tsunami sand layers are often overlain by silty sediments, known locally as *carse*, that are estuarine sediments deposited during the mid-Holocene sea-level highstand. Prior to undertaking the GPR surveys reported here, we anticipated that the silty estuarine sediments overlying the tsunami sand would cause attenuation of the GPR pulse, resulting in relatively poor results. The results reported here are better than we expected. One possible explanation for this is that the fine-grained, silty sediments in Scotland are relatively immature following removal of weathered rocks from the Scottish Highlands during repeated Quaternary glaciations. The hypothesis is that repeated glaciations eroded all weathered regolith from the Scottish Highlands, taking with them clay minerals that are commonly associated with the attenuation of GPR. The result is that the fine-grained, silty sediments supplied to the east coast estuaries of Scotland lack the clay minerals that would have resulted from prolonged chemical weathering in a humid temperate climate.

4.1. Sediment Supply

An outstanding feature of the Storegga tsunami deposits around the Dornoch Firth is the thickness of the sand layer, which is greater than those observed in recent tsunami deposits.

The sand layer at Creich was described as 1.6 m thick [40], and this thickness was confirmed by the GPR survey and boreholes in this study. Boreholes at Dounie showed that the sand layer reaches a thickness of 1.39 m [43], and similar thicknesses are reported here. Comparison with tsunami sand layers from recent tsunamis such as the 2011 Tohoku tsunami and the 2004 Indian Ocean tsunami (IOT), where the maximum reported sediment thickness is 0.52 m for the Tohoku-oki tsunami on the Sendai plain in Japan [50], although a maximum of 0.3–0.4 m is more common [51], with one report of 0.6 m from a local scour fill [52]. Elsewhere, on Sabusawa Island, Japan, ref. [53] reported 0.8 m, while on the Kuril Islands, a maximum of 0.14 m was reported [54]. Sediments deposited by the Indian Ocean Tsunami (IOT) are widely reported. In Thailand, maximum thicknesses of 0.25 and 0.3 m were reported by [55,56], respectively. In Sri Lanka, 0.66 m was reported by [57,58], with a report of a maximum of 0.4 m in Tamil Nadu, India. On Sumatra, which was the most proximal landfall for the IOT, a thickness of 0.82 m was reported by [59], while [60] reported 0.5 m of sediment near Meulaboh. The borehole results compiled by [2] as well as those recorded here show that the Storegga tsunami sediments are nearly twice as thick as those of the IOT or Tohoku-oki tsunamis. The very thick sand layers suggest that there must have been a large source of fine sand available within the Dornoch Firth at the time of the

tsunami, most likely stored in intertidal sand bars like those found in the area today. After breaking, a tsunami wave propagating into shallow water is led by a bore [61], which is associated with strong mixing and massive sedimentation processes upriver [61]. Such intense mixing and deposition of fine sand from suspension is envisaged as a method for the thick tsunami sand layers at Creich and Dounie, combined with a greater sediment supply from intertidal sand bars in the Dornoch Firth, with the tsunami funnelled into the river valley, which acted as a tsunami highway [62].

It is worth noting that the palaeogeography of the Dornoch estuary at the time of the tsunami would have been different because the beach ridges and dunes at Morrich More at the eastern end of the estuary would not have been present because they are younger deposits [63,64]. This would have left a wider entrance to the Dornoch Firth, enabling the tsunami wave to extend into the estuary. The Dornoch Firth is an estuary confined within a ria with wide areas of unconsolidated, fine-grained sand in intertidal sand bars. In comparison with the IOT in Thailand, the tidal range is similar but the geomorphology is different. The beaches on the Andaman Sea in Thailand are relatively short and steep [65] and the tidal inlets are surrounded by mangroves, both of which will have contributed to different tsunami wave behaviour and resulting sedimentation. At Sendai in Japan, the beach sand is medium to coarse sand while the dunes are medium to fine sand [66], the beach slope is relatively low at 0.047 [67], tidal range is lower, and the sand source is linear, restricting the source area of sand to a linear strip of beach and sand along the coast. In contrast, the tidal sand bars in the Dornoch Firth extend up to 19 km inland, increasing the potential source of fine-grained, unconsolidated, sand-sized particles that are found in the tsunami sand layer.

4.2. Thickness Changes at Creich

The GPR survey provides additional insight into the thickness of the tsunami sand layer at Creich. The sand layer is shown to thicken and thin inland, as well as along the strike. It is far from the gentle thinning interpolated from borehole data illustrated by [40]. Instead of a pair of spits across the mouth of the embayment, the GPR does not show evidence for a spit on the southern side; instead, there appear to be channel scours in this area (Figure 7). Furthermore, a spit attached to the northern margin is consistent with a westerly longshore drift when the entrance to Dornoch Firth was open to northeasterly waves [63]. When tsunami waves enter an embayment, they will commonly wash over beach ridges and dunes, but the inflow has to be followed by an outflow as the water returns to the sea. During the return flow, the water tends to follow pre-existing topographic lows, converging on channels and inlets and reaming out the channel, causing extensive scour. We speculate that the channel formed at the southern end of the profiles might be the remnants of the tsunami outflow. However, most of the observed changes in thickness can be attributed to the differential compaction of underlying intertidal channels and intervening fine-grained marsh deposits, combined with later erosion by intertidal channels during the Holocene highstand, which create an irregular base and top surface to the tsunami sand layer (Figures 7 and 8).

4.3. Sea-Level and Geomorphological Changes

In Scotland, the Holocene transgression coincided with a glacial isostatic rebound to produce a sea-level curve with a mid-Holocene highstand and subsequent regression because the rate of glacial isostatic uplift exceeded the rate of sea-level rise during the last 5000 years, e.g., [68,69]. At the time of the Storegga tsunami, 8150 cal. yr BP [4], sea-level mean high water spring tides (MHWST) at Wick were around -4 m [2]. In the Dornoch Firth at Creich, sea level was at $+2$ m OD [2], which compares with present day mean high water spring tides (MHWST) at 2.3 m at Meikle Ferry, which is 8 km from Creich. In the meantime, sea level in the Dornoch Firth rose to approximately 6 m or 7 m OD during the mid-Holocene highstand [40,42]. During the mid-Holocene highstand, fine-grained estuarine sediments were deposited over the Storegga tsunami sediments. This had the

effect of burying the tsunami deposits by over a meter of silty sediments, known locally as carse. In addition, there have been other geomorphological changes within the Dornoch Firth that are likely to have influenced the propagation of the tsunami; most notably, the extensive beach ridge plain and coastal dunes at Morrich More on the south side of the firth formed later, after the mid-Holocene highstand [42]. Similarly, the spit at Dornoch Point on the north side of the estuary probably formed during the Holocene highstand [42] and thus post-dates the Storegga tsunami. The spit at Dornoch Point and beach ridges at Morrich More currently restrict the width of the entrance to the Dornoch Firth to less than 2.5 km (Figure 1). At the time of the tsunami, the entrance to the Dornoch Firth would have been much wider, close to 9 km, allowing waves to penetrate further into the estuary [63,64]. In addition, spits within the firth at Ardjachie were also interpreted to have formed after the tsunami [42] and thus would not have obstructed tsunami flow within the firth.

The elevation of the spits within the Dornoch Firth is used to estimate their relative age in relation to the early Holocene transgression and mid-Holocene highstand [42]. The relative age of the spits appears to be confirmed by the stratigraphic interpretation of the GPR profile at Ardmore, where an older, lower elevation spit appears to have been eroded and overwashed by the Storegga tsunami, while younger, higher-elevation spits appear to overlay the tsunami erosion surface because they were formed later, during the mid-Holocene highstand. An additional product of the GPR survey is the observation that the older spit is dominated by washover deposits dipping inland, while the younger spits are dominated by progradational, seaward dipping reflections. This change in reflection pattern is attributed to the relative sea-level changes at the time when the spits were formed, with washover dominating during the early Holocene transgression and progradation during the later sea-level highstand. While it is possible to speculate that the post-tsunami spits benefitted from sediment released during the tsunami, a response to sea-level change is preferred, with overwash associated with transgression and progradation associated with sea-level highstand. In this conceptual model, the sediment supply remains almost constant, and it is the change in accommodation space determined by relative sea-level change that determines the difference in spit stratigraphy.

5. Conclusions

GPR surveys within river valleys (Wick) and drained estuarine sediments around the Dornoch Firth provided high-quality images of the Storegga tsunami sediments even in areas where the tsunami sand layer is overlain by around 1 m of silty sediments. This may, in part, be due to the relative immaturity of Holocene sediments along the east coast of Scotland. In general, the reflections from the tsunami sand layers are continuous and undulating, but we have not found any unique property of the reflections or reflectors that would provide unequivocal identification of tsunami deposits from GPR surveys alone. The outstanding thickness of the Storegga tsunami deposits around the Dornoch Firth is attributed to an abundant supply of fine-grained sand from adjacent intertidal sand bars. This contrasts with the Storegga tsunami deposits on Shetland, which are much thinner due to a limited sand supply. Erosion of the tsunami deposits is widespread and likely contributed to a miscorrelation between boreholes at Wick. At Creich, the erosion by tidal channels combined with differential compaction and deposition over an irregular buried topography resulted in a complex pattern of thickness changes in the tsunami sand layer. At Dounie, the sand layer is locally eroded by river channels. This includes a simple channel cut and fill as well as river deposits with lateral accretion surfaces. These results contrast with previous statements that the sand layers in estuarine settings show, in general, little evidence of erosion [70] and shows the advantages of shallow geophysical surveys such as GPR to determine the thickness and continuity of tsunami deposits [71].

A change in the stratigraphy of spits was observed on the GPR profile at Ardmore, with landward dipping reflections in the older spit and seaward dipping reflections in the younger spits. This change in reflection pattern is attributed to the contemporary sea-level changes with the older spit formed during a transgression and the younger spits forming

during the mid-Holocene sea-level highstand. Thus, overwash of the spit is associated with transgression, while progradation is associated with the later highstand, most likely due to changes in the balance between sediment supply and accommodation space due to sea-level rise.

Author Contributions: Conceptualisation, C.S.B.; data collection, L.K.B., R.S. and C.S.B.; data processing and interpretation, L.K.B., R.S. and C.S.B.; original draft preparation, L.K.B.; writing—review and editing, C.S.B. All authors have read and agreed to the published version of the manuscript.

Funding: This project was funded by the London NERC DTP. NERC grant number NE/L002485/1.

Data Availability Statement: The original contributions presented in the study are included in the article further inquiries can be directed to the corresponding author.

Acknowledgments: Thank you to George Connor, Gavin Suggett, Inus Le Roux, Ewen Simpson, and Kenny for access to their land.

Conflicts of Interest: The authors declare no conflict of interest.

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