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Research Article

Submerged bedrock shore platforms, Orkney Islands, UK: A new record of significant, though chronologically uncertain sea-level change and coastal erosion

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ABSTRACT

Reconstructions of sea level change in NW Europe are primarily based on records of relative sea level (RSL) recovered from terrestrial environments, above modern sea level. This deficit in marine-based records results from the highly limited number of sea level indicators observed in modern submarine settings, as well as the often-limited absolute chronology information available. This sampling bias introduces significant uncertainty in former RSL predictions, negatively impacting efforts to accurately model ice-sheet histories and isostatic response. Here we present new seabed mapping data (i.e. high-resolution multibeam bathymetry) from northern Scotland to address this data gap. Encircling the Orkney Islands we identify an exceptional sequence of submerged terraces ranging from -5 to -95 m below modern sea level, carved in bedrock. We interpret these bedrock terraces as relict shore platforms, based on their spatial distribution and a range of geomorphological characteristics. Shore platform development was linked to contemporaneous landward coastline erosion and cliff formation, and each landform pair (i.e. terrace = shore platform and accompanying seacliff / escarpment) likely represents a single sea-level stillstand event of considerable duration (possibly millennia). These wide and well-preserved shore platforms attest to formation during multiple, separate periods of RSL stillstand, and we estimate that 5–7 RSL stillstands are recorded offshore Orkney. We discuss their potential age – spanning more than the last glacial cycle (i.e. Middle - Late Pleistocene) – and explore the wider implications for Quaternary coastal erosion and sea-level change in the region. This study shows how marine geological data and geomorphological analysis can be used to identify palaeo-sea-level indicators within a glacio-isostatically complex region. Despite a current lack of absolute chronological constraint, we believe these observations may provide crucial information towards understanding sea level change within the NW European region.

1. Introduction

Records of former sea-level change along the NW European margin have primarily been reconstructed from terrestrial sites (e.g., Shennan et al., 2018; Creel et al., 2022), and therefore largely exclude submarine information. This sampling bias towards evidence available above modern sea level limits the scope of relative sea-level (RSL) reconstructions by reducing the elevation range of potential RSL indicators. Research in lower-latitude regions, where geological archives are typically below present-day sea level, has demonstrated the value of offshore records for deciphering RSL change (e.g., Belknap and Mart, 1999; Yokoyama and Purcell, 2021). In particular, recent studies have demonstrated the potential for using advances in marine geophysical observations at greater depths to improve our understanding of the amplitude and timing of former sea-level changes (e.g. Brooke et al., 2017; Cawthra et al., 2018; Ricchi et al., 2018; Bilbao-Lasa et al., 2020; Deiana et al., 2021). Understanding lower than present sea levels has important implications for constraining Earth system response to ice sheet volume changes (Lin et al., 2021), informing submarine archaeology and palaeo-geography (Bailey and Cawthra, 2023), as well as deciphering tectonic movements and deformation (Bloom and Yonekura, 2020).

Within submarine settings a range of erosional and depositional landforms may be used to identify the elevation position of former

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coastlines, and reconstruct palaeo-sea levels. These include deltaic deposits, drowned barrier beaches, erosional notches, marine terraces and (wave-cut) shore platforms (Lebrec et al., 2022, and references therein). To date, the limited work to reconstruct former sea levels offshore Northwest Europe has largely focused on depositional records, e.g., transgressive marine sands and muds overlying terrestrial sediments such as in the southern North Sea and Irish Sea Basins (Shennan et al., 2000; Hijma and Cohen, 2019; Plets et al., 2019; Cohen et al., 2021). By comparison, there has been only limited work to use submerged coastal landforms such as shore platforms and relict shorelines (Stoker and Graham, 1985; Rokoengen and Dekko, 1993; Westley et al., 2011), in part owing to the limited availability of high-resolution bathymetry data.

This study adopts a geomorphological approach (new mapping and morphometric analysis) to characterise a series of submarine palaeo sea-level indicators around the Orkney Islands, offshore northern Scotland, to improve our knowledge of relative sea-level change along the NW European margin (Fig. 1). Unlike observations from 'far field' locations with respect to distance from high-latitude ice loads, observations of RSL from offshore Orkney are complicated by glacio-isostatic processes, namely crustal subsidence / uplift associated with loading and unloading of overlying and nearby palaeo British-Irish and European ice masses (Bradley et al., 2023). However, RSL data from locations proximal to former ice sheets are critical for the development of detailed and accurate geophysical and ice models (e.g. Shennan et al., 2018; Bradley et al., 2023). These models, alongside advances in ice-sheet modelling, allow for better understanding of the rate and magnitude of ice-sheet mass balance changes under different climate regimes. Glacial-isostatic adjustment (GIA) modelling of post-Last Glacial Maximum (LGM) and Holocene RSL change in Orkney suggests that RSL may have been ~30–50 m below present during the deglacial period (ca. 16 ka), rising to at, or just above, modern sea level during the Holocene (Bradley et al., 2011; Ward et al., 2016a, b; Scourse et al., 2024). However, there are limited empirical model constraints across much of the domain, with significant variations in model predictions of deglacial RSL elevation (Shennan et al., 2018; Bradley et al., 2023) and deglacial ice extent following the Last Glacial Maximum (Clark et al., 2022) in Orkney and mainland northern Scotland. Furthermore, there are almost no geological constraints on Scottish RSL and ice sheet histories for periods prior to the LGM (Evans et al., 2024). As a result, any newly identified relict coastal features off Orkney will provide potentially important empirical constraints for GIA models of regional RSL change for the northern North Sea Basin and adjacent coasts. Here, we demonstrate the value of examining the submerged landscape record, which frequently reveals well-preserved records of environmental and geological phenomena operating over multiple time-scales (e.g. Dove et al., 2023; Nanson et al., 2023). We use extensive high-resolution bathymetry datasets from around Orkney to identify and characterise a distinct, stepped sequence of submerged bedrock terraces, that we classify as relict shore-platforms, marking multiple palaeo sea-level stillstands of considerable duration. We go on to discuss their possible age and explore the wider implications for Mid-Late Pleistocene sea-level change and coastal erosion in

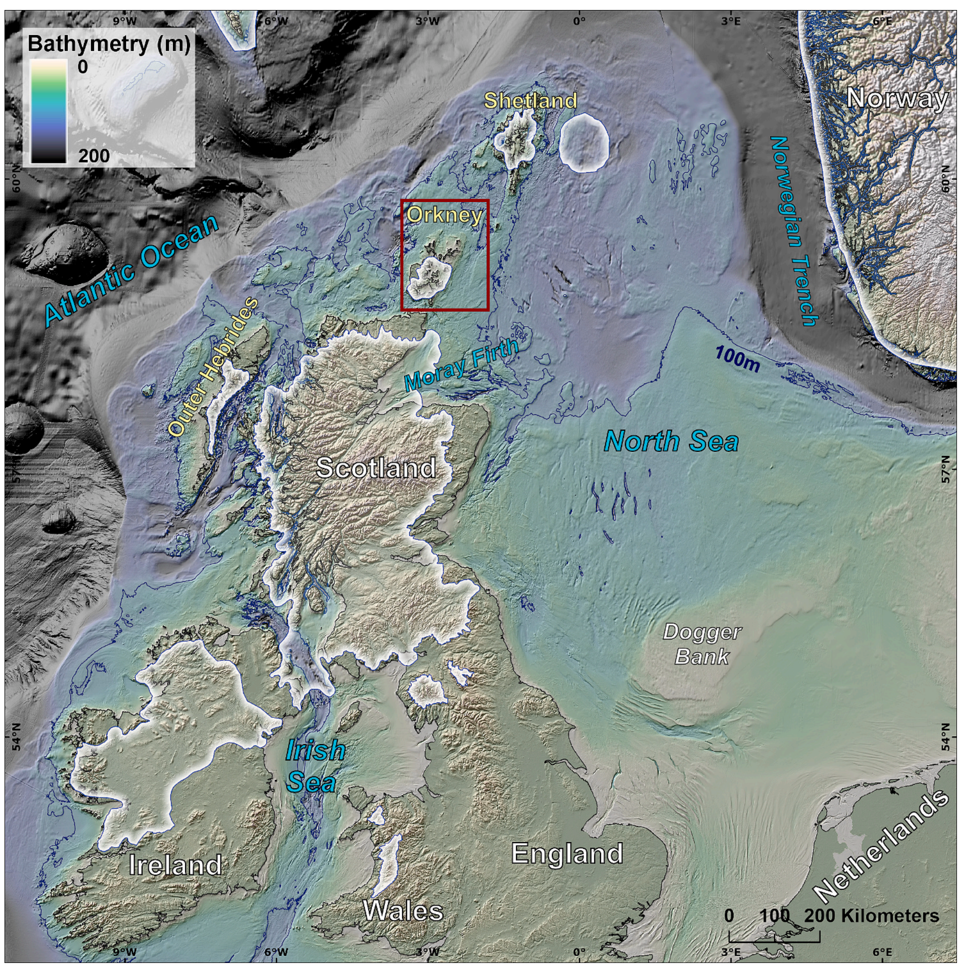

Fig. 1. Orkney study area (red box) shown together with regional bathymetry data (EMODnet), as well as reconstructed ice sheet limits at 17kya (Clark et al., 2022). 100 m depth contour shown for reference. Figure contains EMODnet bathymetry (©) European Union, available under CC BY 4.0. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

northern Scotland and the North Sea Basin.

2. Study site and geological setting

2.1. Location and physiography

The Orkney Islands are located on a regional bathymetric high that extends from the Scottish mainland north-northeast towards the Shetland Islands (Fig. 1). Orkney comprises a group of over 100 islands within an area of ca. 3000 km^2 at the hydrographic boundary between the North Atlantic Ocean to the west and the North Sea to the east. This study focuses on the seabed immediately offshore from the islands, investigating an area of ca. 1000 km^2. Seabed depths within the study area reach ~120 m below present-day sea level, with the seabed generally deepening away from the NE-SW-oriented structural high of the Orkney-Shetland Platform (Fig. 1). The geomorphology of the seabed around Orkney attests to a range of geological and environmental processes that have operated, in isolation or in combination, over significantly different timescales (e.g. tectonism, glaciation, hydrodynamics, climate) (Andrews et al., 1990; Hall and Hansom, 2021).

Marine geological and seafloor mapping around northern Scotland, utilising high-resolution bathymetry data reveals a complex suite of lithological substrates, geomorphological features and benthic habitats at seabed (e.g. Downie et al., 2016; Bradwell et al., 2021; Stewart et al., 2021; Utley et al., 2023; Dove et al., 2023). Superimposed on the regional-scale physiography around Orkney, the medium (<1 km) and finer-scale (<10 m) seabed relief is highly variable (Fig, 2a). The shallow continental shelf (ca. <100 m) around the Orkney Islands hosts extensive exposures of rugose bedrock, a wide range of glacial landforms, as well as Holocene marine sediments and potentially mobile bedforms (Downie et al., 2016; British Geological Survey, 2025). Bedrock at seabed is largely swept free of sediment by the high-energy hydrodynamic environment operating around the islands (Ward et al., 2016a, b; Hashemi et al., 2015). Within the bedrock-dominated intra-island areas, aggradational sediment deposits (i.e. not associated with bedforms) are observed in less-exposed locations and sheltered basins away from prominent tidal streams (Bates et al., 2013). Further offshore and away from the Orkney platform, sediments are found to be thin or absent, with previous sub-surface mapping (based on seismic stratigraphy and sediment cores) revealing unconsolidated sediment thicknesses of typically 1–5 m (and nowhere in excess of 10 m thick) (British Geological Survey, 1984; Holmes et al., 2004).

2.2. Bedrock geology and structure

The bedrock geology of the study area is comprised almost entirely of Devonian sedimentary rocks (e.g. sandstones, flagstones, siltstones) with occasional subordinate lavas of the Middle Devonian and intrusive Permian dykes (Mykura, 1976; British Geological Survey, 1985). The Orkney Islands also host minor outcrops of older crystalline basement (Proterozoic granites, gneisses and metamorphic rocks) in the far west of Mainland Orkney (Strachan, 2003). The distribution of these ancient Proterozoic granites offshore is currently not well known (Stoker et al., 1993).

The region has played host to multiple tectonic cycles, with structural inheritance having a significant impact on the regional-scale seabed geomorphology. The dominant Old Red Sandstone (Devonian) rocks were deposited, and later deformed, during the latter stages of the Caledonian Orogeny (Mykura, 1976; Bird et al., 2015); it is probable that much of this tectonism was influenced by inherited pre-Caledonian structural fabrics (Bird et al., 2015; Schiffer et al., 2020). Tectonic rifting processes during the Devonian, and again in the Permo-Carboniferous, resulted in the relative structural high (oriented ~NE-SW) of which the Orkney Islands are the present-day subaerial expression (Wilson et al., 2010; Utley et al., 2023). Associated, relatively large, fault-bounded basins are found to the west (e.g. West Orkney Basin), where seabed depths reach a maximum of 200 m below present-day mean sea level, and to the east of the study area. An adjacent NNE-SSW-oriented bathymetric basin is bounded by the prominent Walls Boundary Fault that projects NNE, close to the present-day coastline of Orkney, and continues to the Shetland Islands (Figs. 1, 2) (Andrews et al., 1990). Through the Cenozoic it is likely that the area experienced further episodic tectonic uplift (and potentially during the Plio-Pleistocene) (Evans, 1997; Japsen and Chalmers, 2000; Praeg et al., 2005; Anell et al., 2009). However, the precise timing of these events and their location-specific uplift amplitudes and rates are not well constrained.

2.3. Quaternary geology, modern coastal and marine processes, and relative sea-level change

The Quaternary geology of the Orkney Islands and surrounding submarine areas is complex and discontinuous with little or no stratigraphic correlation currently existing between the onshore and offshore deposits. Onshore Quaternary deposits are relatively well studied and mainly fall within the *Banffshire Coast, Caithness and Orkney Subgroup* of the *Caledonia Glacigenic Group* (McMillan et al., 2011; Merritt et al., 2019). Offshore deposits are still poorly defined. Mid to Late Pleistocene deposits east of Orkney sit within the *Reaper Glacigenic Group*, whilst those to the west on the Atlantic-facing continental shelf are within the *Hjaltland Glacigenic Group* (Stoker et al., 2011). On the Orkney-Shetland platform and between the islands themselves where the Quaternary cover is very thin and patchy, no formal stratigraphic assignment has been made. A number of notable geomorphological seabed features chart the growth and recession of the last ice sheet / ice cap complex to cover the islands (Bradwell et al., 2008; Merritt et al., 2019; Stewart et al., 2021). These glacial landforms include subglacially streamlined forms, ice-marginal moraines of various size and meltwater channels. While glaciation has potentially impacted this region several times since the earliest Quaternary (~2.6 Mya) (Ottesen et al., 2014; Newton et al., 2024), the thin superficial sediment cover (generally <5 m) and coherent moraine pattern across the region suggest that the majority of the offshore glacigenic landforms probably formed during the most recent glacial episode (i.e. Marine Isotope Stage 2–3 (~31–17 kya) (e.g. Bradwell et al., 2008, 2021; Hall et al., 2016; Clark et al., 2022).

Well-developed shore platforms currently exist along Orkney's modern coast at, or close to, present-day sea level (e.g. Smith et al., 2019; Hall and Hansom, 2021). Some of these platforms are actively forming, though some are deemed to be relict or inherited features. Orkney's rocky coasts and its geographic location are strongly conducive to shore platform development, with exposure to a highly energetic hydrodynamic regime (wave and tidal) as the main erosion agent (Hashemi et al., 2015). These conducive conditions have likely prevailed for many millennia (Ward et al., 2016), at least since MIS 2 deglaciation, ca. 17–15 ka BP (Bradwell et al., 2021).

Marine sediments and bedforms, of Holocene through modern age, discontinuously overly both bedrock and glacial sediments across the area, and grab samples show these seabed sediments to be predominantly composed of gravelly sands and gravels (British Geological Survey, 1984) with localised occurrences of finer sands associated with current-induced bedforms. Marine bedforms include sediment banks, dunes (e.g. megaripples and sand waves), and longitudinal sediment ribbons and furrows. Carbonates also constitute a high proportion of the seabed sediments around the Orkney Islands (Pantin, 1991).

Orkney's position with respect to Late Pleistocene ice-sheet centres has resulted in a complex, hard to constrain, pattern of RSL change (e.g. Shennan et al., 2018; Smith et al., 2019; Bradley et al., 2023). Ice-sheet peripheral regions such as SE England and southern North Sea coasts have seen marine encroachment and decreasing rates of RSL rise throughout the Holocene (Shennan et al., 2018). By contrast, the Orkney landmass and its immediate offshore areas experienced falling RSL to a low of ~30–50 m below modern sea level (trending deeper from south to north) in the aftermath of deglaciation (15–11 ka BP). This was followed

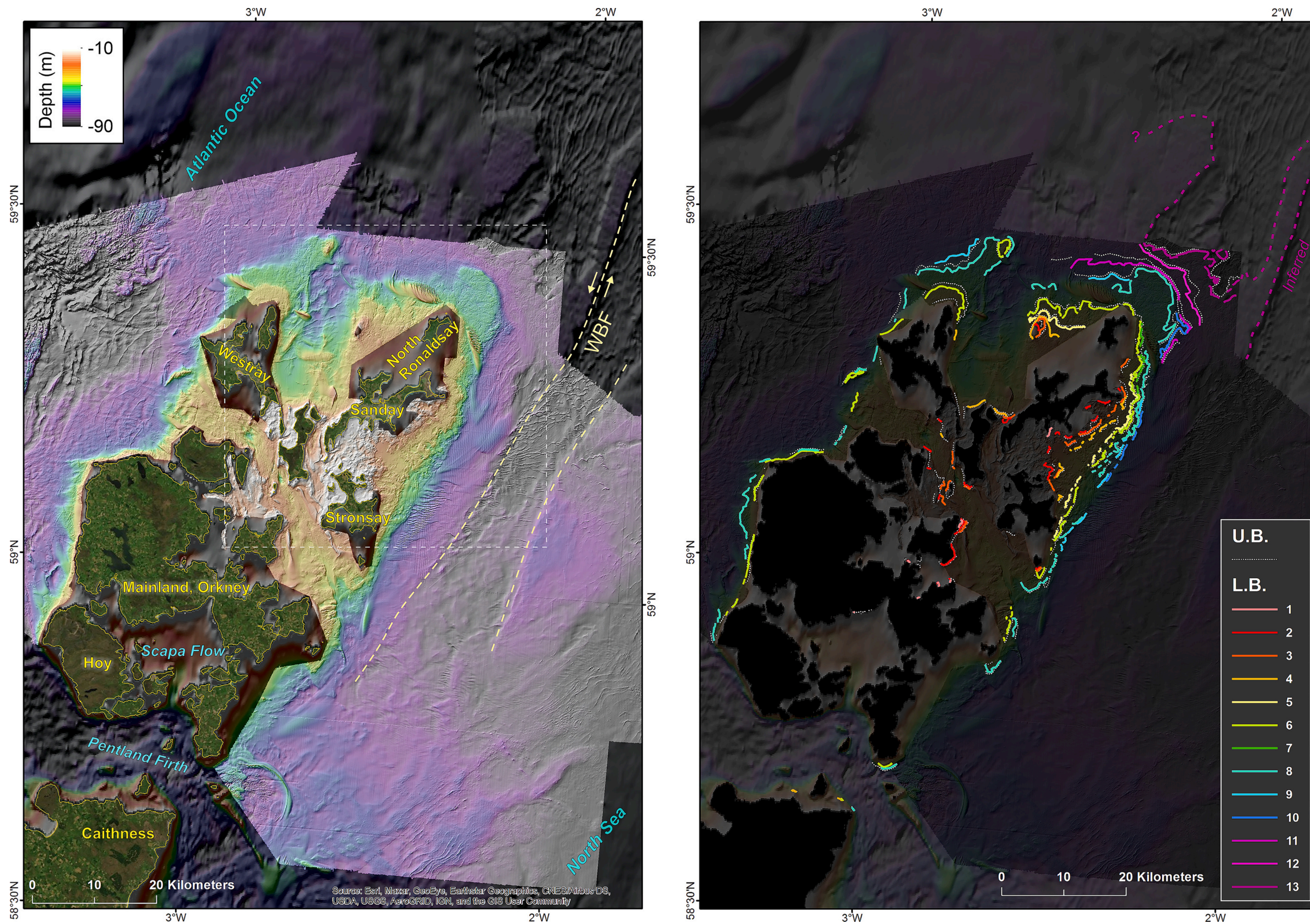

Fig. 2. A) High-resolution bathymetry data (5 m resolution) surrounding the Orkney Islands, Scotland. White-dashed line shows bounding box for Fig. 5. Approximate location of Walls Boundary Fault (WBF) zone also shown. B) Interpreted shore platforms, with upper platform boundary (U.B.) and lower platform boundary (L.B.) shown. (Bathymetry data courtesy of the UK-CHP – Crown Copyright © 2025).

by rising RSL at the start of the Holocene, with the rate of barystatic sea-level rise due to the melt of far-field ice sheets outpacing the local rate of isostatic rebound, from 11 to 6 ka BP (Bradley et al., 2011; Scourse et al., 2024). In the Mid to Late Holocene low-elevation raised beaches (1–3 m above modern sea level) and transgressive marine sediments on Orkney indicate a slight RSL fall over the last 3–5 ka due to ongoing isostatic rebound (Hall et al., 2016; Shennan et al., 2018; Smith et al., 2019). In submerged and inter-tidal coastal areas, energetic wave conditions and strong tidal currents are likely to have persisted throughout the Holocene (Ward et al., 2016), regularly mobilising sediments and preventing significant nearshore deposition. Long-term monitoring studies suggest that large sediment banks (e.g.'Sandy Riddle' east of Pentland Firth) may be geographically (quasi)-fixed by the interaction of bedrock headlands, seabed topography and persistent currents (Dyer and Huntley, 1999; Holmes et al., 2004; Armstrong et al., 2022).

Further north, around Shetland, the seabed displays a prominent and extensive submerged rock platform at −70 m to −82 m elevation. Flinn (1964, 1969, 1977) identified this bathymetric feature and other, less well-developed platforms at −45 m and − 15 m, using low-resolution depth-sounding maps and unpublished Hydrographic Office charts. Extending this mapping, using early seismic reflection profiles, Flinn (1973) identified a single submerged platform around northern Orkney at −60 m, which may also relate to the platform around Shetland. These prominent, wide, submerged platforms, first identified in the 1960s, have been tentatively associated with former low sea levels, possibly during Marine Isotope Stages (MIS) 3 and/or 5 (Smith et al., 2019) – although their extent and age remains very uncertain. Much less equivocal are a number of shore platforms, eroded in bedrock, around the modern coastline within the inter-tidal zone of the Orkney Islands (Hall and Hansom, 2021). These features are still actively forming and therefore partly Late Holocene in age, but their geographical extent, extensive width and, in places, till covering suggest that their form is largely inherited from pre-glacial or interglacial times when sea levels were at, or close to, present elevation (Smith et al., 2019; Evans et al., 2024).

3. Methods and data acquisition

3.1. Multibeam bathymetry data

Multibeam (MBES) bathymetry data were collected by the Civil Hydrography Programme (CHP) for nautical charting and safety-at-sea purposes. These publicly available data (https://datahub.admiralty.co.uk/portal/apps/sites/#/marine-data-portal) were acquired over multiple survey campaigns (HIs 1072, 1122, 1137, 1202, and 1218) between 2004 and 2008. For this study, individual datasets were mosaicked together to form a single digital bathymetric model (DBM), gridded to a horizontal resolution of 5 m. All water depths are presented with respect to the chart datum of Lowest Astronomical Tide (LAT). The vertical resolution of the data is accurate to less than 20 cm, and better in shallower waters. The data cover most of the offshore areas surrounding the Orkney Islands, as well as portions of the sheltered inter-island 'internal water' areas (in places as shallow as -2 m) (Fig. 2a), with the area of interest covering approximately 2700 km^2. Co-registered MBES backscatter data were used in places to support interpretations, as well as legacy BGS sample data (e.g. grab samples, boreholes etc) and geological maps (http://mapapps2.bgs.ac.uk/geoindex_offshore/home.html). Coarser-resolution bathymetry data (~115 m spatial resolution) covering the entire continental shelf (EMODnet Digital Bathymetry, 2022), as well as previously performed predictive bedrock mapping were also used to provide further regional context (Downie et al., 2016).

3.2. Geomorphological mapping

MBES bathymetry and supporting data were loaded into a GIS for geomorphological visualisation, interpretation and mapping.

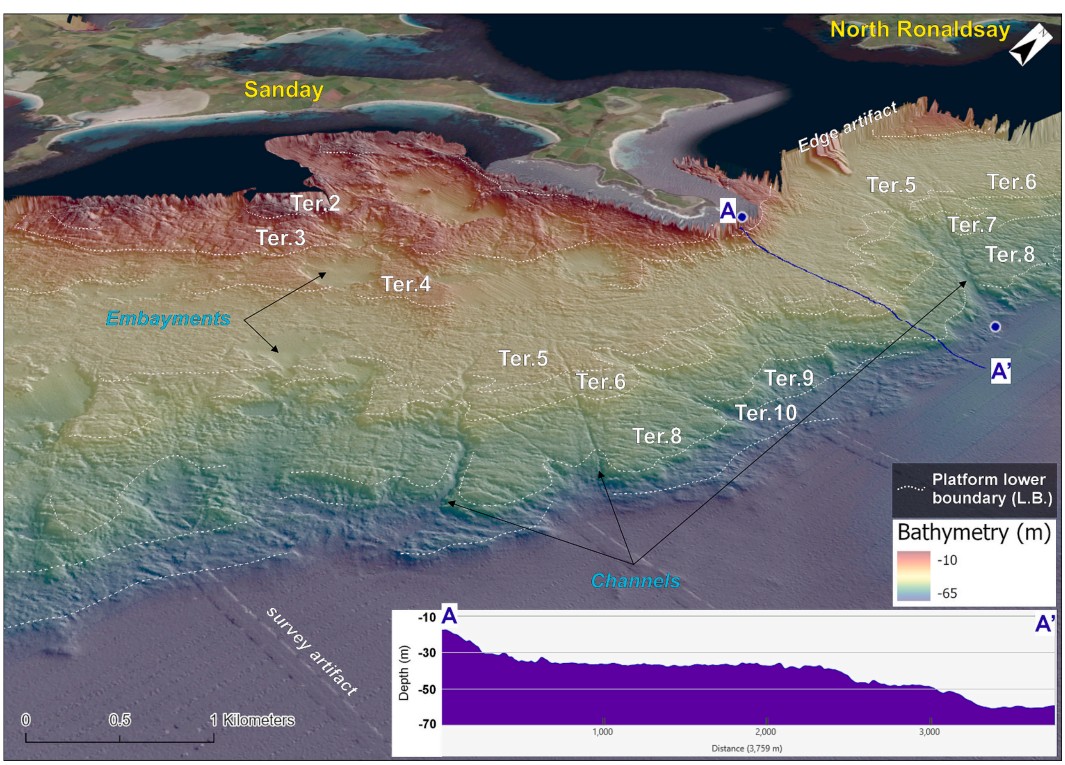

Fig. 3. 3D perspective (view from approximately East to West) of the bathymetry and interpreted shore platforms (lower platform boundaries: white dashed lines). Terrace (Ter.) = shore platform + landward escarpment. Elevation cross-section (along blue profile line) demonstrates terrace morphology. Note channels and embayments eroded into terraces. (Bathymetry data courtesy of the UK-CHP – Crown Copyright © 2025) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

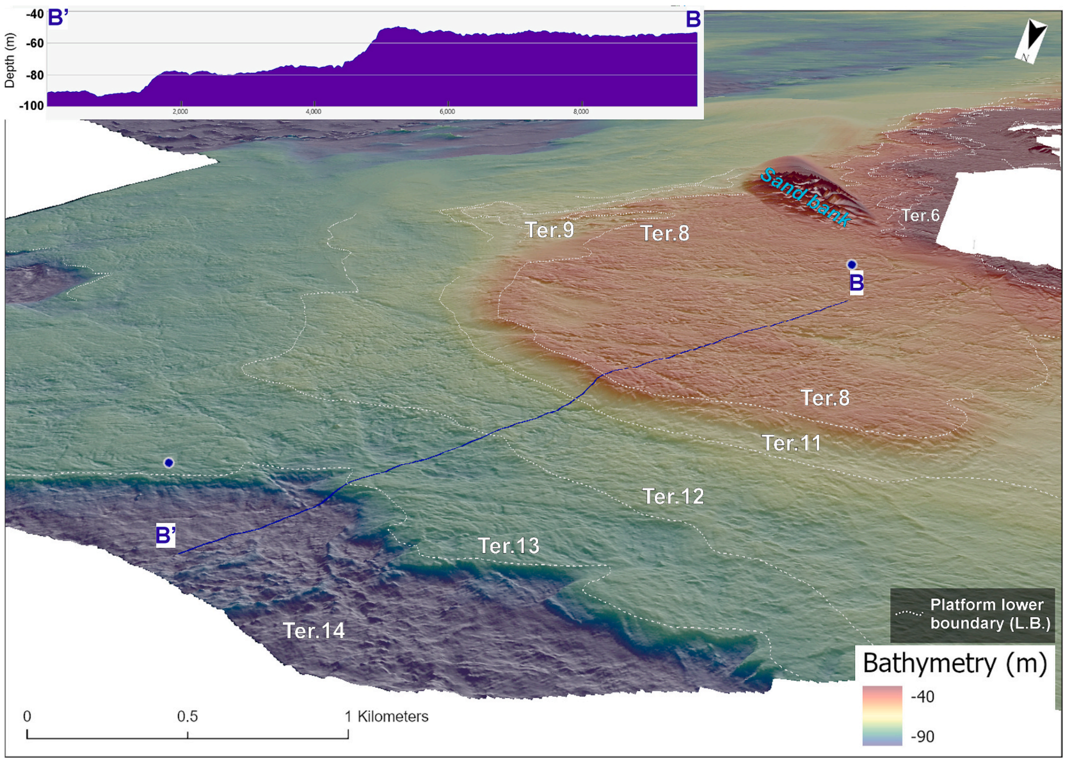

Fig. 4. 3D perspective (view from approximately North to South) of the bathymetry and interpreted shore platforms (lower platform boundaries: white dashed lines). Terrace (Ter.) = shore platform + landward escarpment. Elevation cross-section (along blue profile line) demonstrates terrace morphology. Note that some mapped features (e.g. Ter. 11 & 12) may be constituent parts (of platforms) rather than distinct, individual terraces. (Bathymetry data courtesy of the UK-CHP – Crown Copyright © 2025) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Morphometric layers (e.g., slope, rugosity, relative topographic index, and hillshade rasters with different lighting angles) were derived from the mosaicked bathymetry data to allow detailed geomorphological investigation of seabed features, as well as viewing the bathymetry in 3D (Figs. 3,4). The dynamic range of the bathymetry colour ramp was regularly adjusted to better detect morphological features within specific depth zones of interest. As detailed further within Section 4, we observe a distinct terraced morphology extending offshore from Orkney. These terraces comprise flat to shallow-dipping platforms, separated by relatively steeper sloping escarpments.

To best characterise the features and potentially investigate terrace development, we have mapped both the upper and lower boundaries of the terrace platforms for visualisation and analytical purposes (Figs. 2b,5) (e.g. Ricchi et al., 2018). This has proven to be an effective way to identify and discriminate between individual terraces based on elevation; provide clarity for classification purposes; and enable the calculation of simple terrace metrics (e.g. elevation, depth distribution, terrace width, etc.) (Figs. 6–8). We have not explicitly mapped the terrace escarpments (steeper slopes). The upper platform boundary (UB) is mapped at the landward edge or perimeter of each platform, and the platform's lower boundary (LB) is delineated by the seaward (convex) break-of-slope of the platform (Fig. 9). Because there is commonly more morphological complexity observed at the base of the bounding escarpments (e.g. ridges, hummocks, ramps – potentially relating to mass-movement processes), the UB is not always located precisely at the escarpment base but further seaward at the clear edge of the uninterrupted platform. Geomorphic continuity was used to identify and map terraces, with geomorphic character (e.g. width, slope, surface texture) and terrace elevation (or water depth) important distinguishing criteria.

Geomorphological terraces (via bounding platform breaks of slope, i.e. UB and LB) were mapped via manual digitisation within the GIS environment. Semi-automated mapping is effective for delineating many geomorphological features (e.g., current-induced sediment waves, moraines, pockmarks, etc) (Dove et al., 2023), however, manual interpretation and digitisation was preferred for mapping the terraces due to their variable and rugged bedrock morphology, and their discontinuous nature in places. To aid accurate and consistent interpretation, derived rasters of 'relative topographic position' were prepared to highlight relative bathymetric highs at multiple spatial scales (Whitebox Geospatial - Lindsay, 2016). While we have taken this multi-faceted mapping approach to reduce uncertainty, it must be acknowledged that there remains the possibility of mapping errors (e.g. inconsistent correlation of individual terrace features over broad areas). Unless otherwise stated seabed geomorphological mapping employs the classification scheme presented in Nanson et al. (2023), which provides a comprehensive framework for classifying seabed features of varied geomorphic origin (e.g. coastal, fluvial, glacial).

To further characterise, and better understand the origin and evolution of these submerged terraces, we prepared a number of analytical metrics (e.g. depth distribution, depth vs. latitude, width etc) based on the high-resolution bathymetry data (Figs. 6–8). For example, the mapped terraces are compared to independently prepared histograms of the sampled bathymetry (Fig. 6). To assess platform elevation, water depth was sampled from the bathymetry data raster along the mapped lower platform boundaries (LB).

4. Results

4.1. Submerged bedrock terraces

High-resolution MBES bathymetry data from around Orkney has revealed a stepped sequence of generally coast-parallel bedrock-dominated terraces, between approximately -5 m and -95 m elevation (i.e. below present-day mean sea level (Lowest Astronomical Tide)) (Figs. 2–5). The terraces comprise relatively flat to shallow-dipping platforms of variable width (up to 7 km), separated by narrow steeper

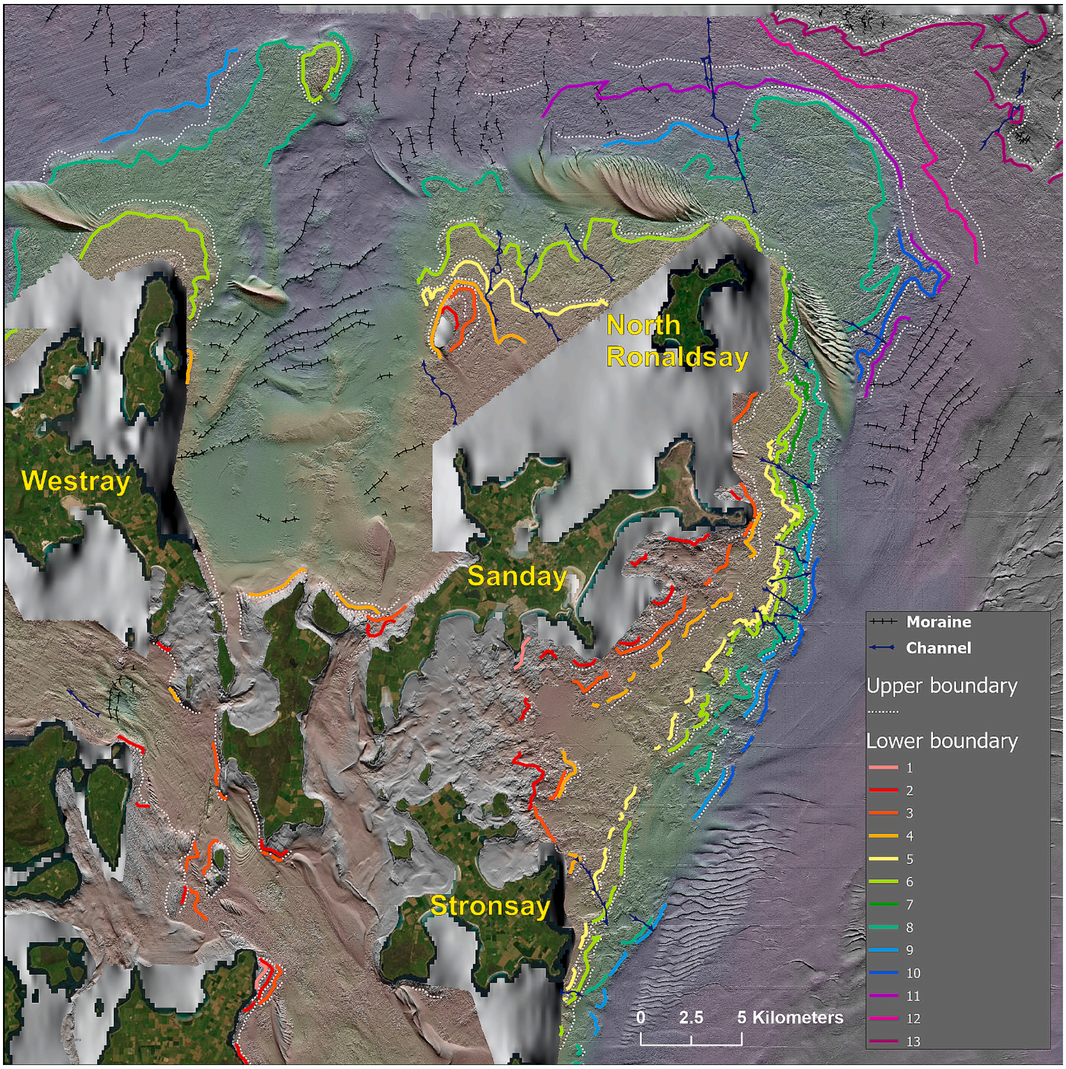

Fig. 5. Zoomed-in map within northern sector of study area showing interpreted shore platforms together with key geomorphic features (glacial moraines, and incised channels), which provide useful information on relative event chronology. (Bathymetry data courtesy of the UK-CHP – Crown Copyright © 2025).

sloping escarpments of variable vertical relief (up to 20 m). While some of the constituent platforms are relatively narrow (e.g. ~100 m wide), several of the platforms are highly planar over extensive areas (>10 km^2). The mapped terraces encircle most of the Orkney Islands; although we observe a greater number of terraces, across a greater depth range, to the north and northeast of the islands (Fig. 2). Twelve distinct terraces (platform + escarpment pairs) have been identified and mapped (Terraces 2–13), with a further two partial terrace constituents, 'Ter1' and 'Ter14', representing the shallowest (LB) and deepest (UB) respectively (Figs. 2, 5). The terrace IDs do not always represent an individual terrace in a specific location, but rather signify terrace(s) interpreted to have formed during a single/shared terrace forming event. For example, Terrace 6 is identified and mapped in several places around the Orkney Islands, although is discontinuous and cannot be traced in an uninterrupted way between the different sites. Some terraces are less pronounced, and more fragmentary than others, but terrace numbers are ascribed where distinct terrace morphology is observed. (The number of probable terrace-forming events discussed in Section 5.3.)

4.2. Individual terrace characteristics

This section provides a brief description of each individually mapped terrace, numbered from shallowest to deepest, defined by the typical elevation of the upper (UB) and lower boundaries (LB) of the constituent terrace platforms (Fig. 5). The water depth values are given as negative (-) elevation values and based on average boundary depths (Fig. 6).

We note that some terraces are better developed and more pronounced than others. Particularly prominent terraces with greater platform width and higher escarpment relief are observed at approximately −34 to -46 m (Ter5 & 6), -48 to -55 m (Ter8), and -70 to -80 m (Ter11–13) (Figs. 6). Terraces 6 & 8 are observed around the study area, and Terrace 13 is limited to the far northeast, though probably persists outside the study area. A well-preserved stepped sequence of terraces is found to the east of Sanday, where up to seven terraces (Ter2–9) are mapped descending to a water depth of around 60 m (Fig. 5). Across the study area, average platform widths range from approximately 200 m to 5000 m. Platform slopes are commonly very shallow, especially on the deeper water terraces, typically ranging from 0.1 to 1°, with bounding slopes/escarpments between approximately 3° and 15°. Escarpment height is observed to be between approximately 2 m and 20 m in vertical relief. Note that relatively minor terraces (i.e. Ter7, 9–12) may not be independent features but constituent parts of more pronounced adjacent terraces (e.g., Ter6, 8, 13). These relationships are explored further in the following sections.

4.2.1. Terrace 1: <-5 m (undefined) (UB) to -6 m (LB)

This is the shallowest (partially) mapped terrace occurring in water depths of up to 6 m (Figs. 2,3,5). It is only sparsely observed and only the

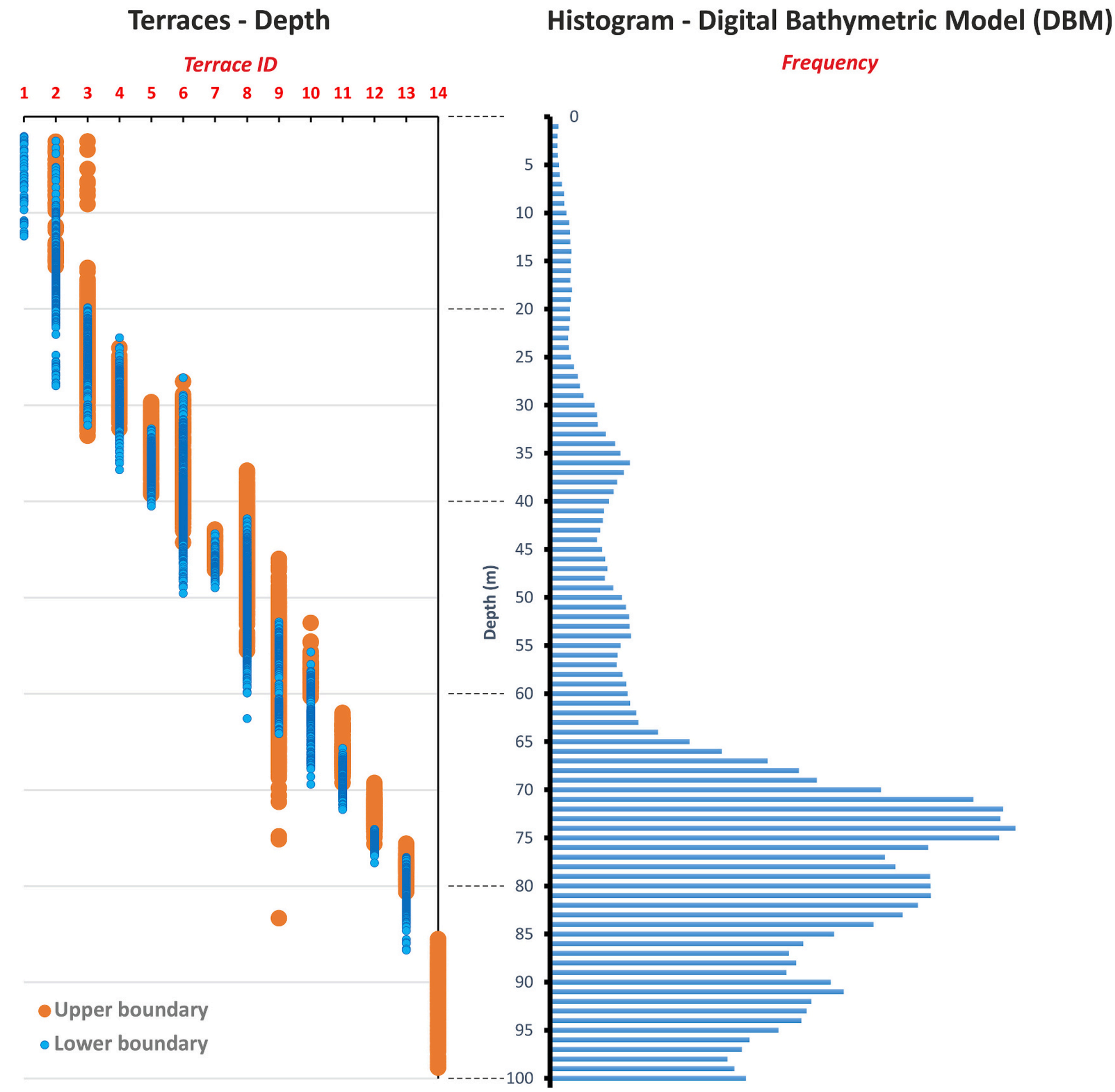

Fig. 6. Platform depth. Left panel shows depth ranges, with values sampled at 100 m interval along mapped shore platform boundaries (upper - orange, and lower - blue). These mapped depths can b contrasted with, in right panel, an independent histogram of the study area bathymetry. Depth scale (metres) applies to both the left (mapped depths) and right (histogram depths) panels. Note that several prominent mapped terraces on the left panel (e.g. Ter. 5–6, Ter8, and Ter11–13; Table 1)) appear correlated with histogram peaks on right panel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

lower boundary (LB) can be defined owing to the limitations of the MBES data. It is notable that Terrace 1 (and Terrace 2) are primarily identifiable by clear escarpments at their seaward terminus. Terrace 1 does not exhibit clear 'platform' morphology but appears more as a shallow step – with a gentle slope (commonly 2–3°) separated by a steeper seaward escarpment (commonly 5–8°).

4.2.2. *Terrace 2: -9 m (UB) to -15 m (LB)*

Terrace 2 is clearly and consistently observed in the eastern Orkney terrace sequence in water depths of 9–15 m (Figs. 2,3,5). As above, the Terrace 2 'platform' is more of a sloping surface than strictly a horizontal 'platform' (with a slope up to ~8°, and relief up to 10 m). Terraces 2 and 3 (and perhaps Terrace 1) are distinguished from the terraces below by their distinctive smoothed bedrock morphology and lack of prominent bedrock fractures, potentially due to their relatively recent age, or a higher degree of glacial abrasion and/or hydrodynamic erosion.

4.2.3. *Terrace 3: -24 m (UB) to -26 m (LB)*

Terrace 3 is the shallowest bedrock terrace with clear platform morphology, presently at 24–26 m water depth, fronted by a well-defined escarpment (Figs. 2,3,5). Terrace 3 has not been smoothed to the same extent as Terrace 2 above, and displays deeper bedrock fractures and numerous irregular-shaped depressions interrupting the platform surface and small indents or embayments in its outer margin.

4.2.4. *Terrace 4: -28 m (UB) to -30 m (LB)*

Terrace 4 has clear platform morphology and a more rugose seabed than Terraces 2 and 3, with deeper and more numerous embayments interrupting its seaward margin (Figs. 2,3,5).

4.2.5. *Terrace 5: -34 m (UB) to -36 m (LB)*

Terrace 5 is generally a wide well-developed platform around Orkney, at 34–36 m water depth, but where narrow is difficult to distinguish from Terrace 6, particularly within the eastern sequence (Figs. 2,3,5). Terrace 5's seaward margin is interrupted by numerous large semi-circular embayments that sometimes expand or 'open out' in a landward direction strongly reminiscent of present-day bedrock coast geomorphology. Terrace 5 is the shallowest terrace incised by palaeo-channels.

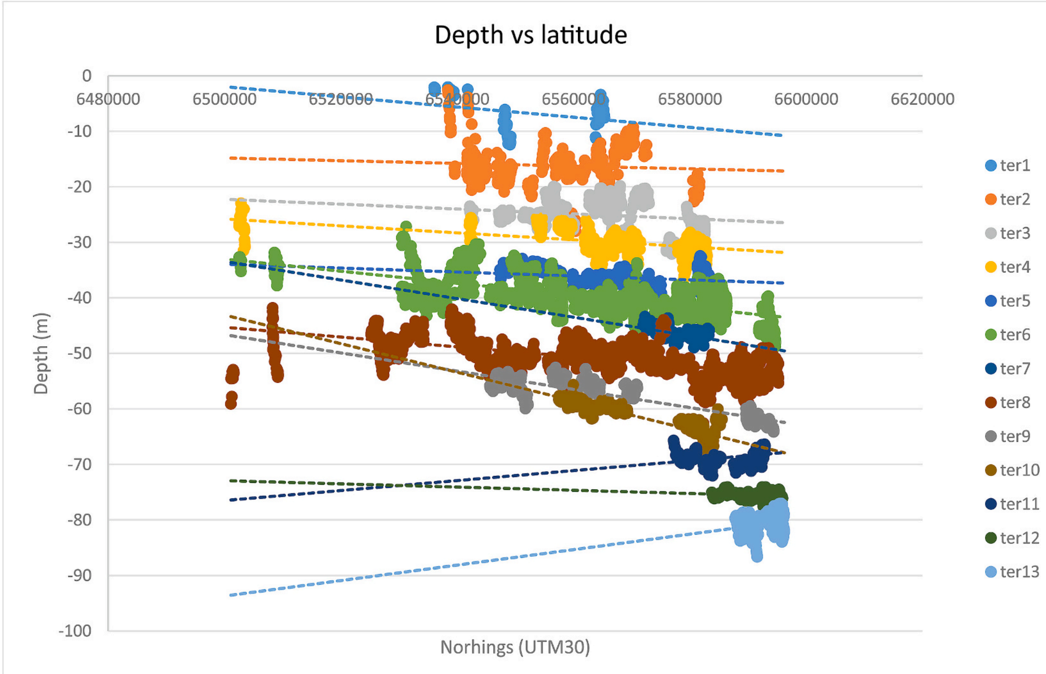

Fig. 7. Platform depth vs. latitude. Lower platform boundary depths plotted against latitude. Reveals general, though variable, increase in platform depth to the north (Excluding terraces 11–13 – limited latitudinal range).

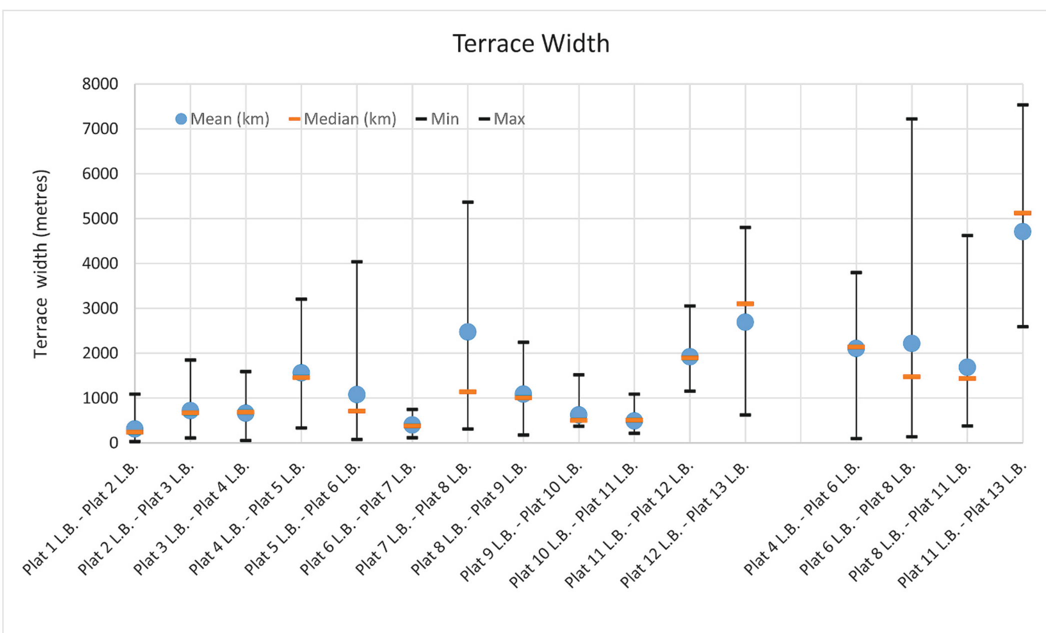

Fig. 8. Platform width. Platform width calculated between lower platform boundaries (L.B.) of adjacent terraces. Left side of plot shows widths of individual terraces, whereas right side shows combined widths of several mapped terraces that may represent single, distinct features (Table 1).

4.2.6. Terrace 6: -36 m (UB) to -39 m (LB)

Terrace 6 is a prominent, extensive, and well-defined terrace to the north and west of Orkney with wide (commonly up to 2 km or more) well-developed platforms and high relief escarpments (up to ~10 m) (Figs. 2–5). However, Terrace 6 is relatively narrow in the east as currently mapped, and as suggested above, can be confused with Terrace 5 or vice versa. Terrace 6 is incised by channels in several locations, and a number of embayments are eroded into its seaward margin (and Terrace 5).

4.2.7. Terrace 7: -45 m (UB) to -46 m (LB)

This is a minor, weakly developed, terrace only sporadically observed in the eastern Orkney sequence (Figs. 2,3,5). Mapped in a water depth of 45–46 m and situated between the prominent Terraces 6 and 8, Terrace 7 may be associated with or sometimes confused with these other terraces.

4.2.8. Terrace 8: -46 m (UB) to -50 m (LB)

Terrace 8 has the most prominent well-developed platform and

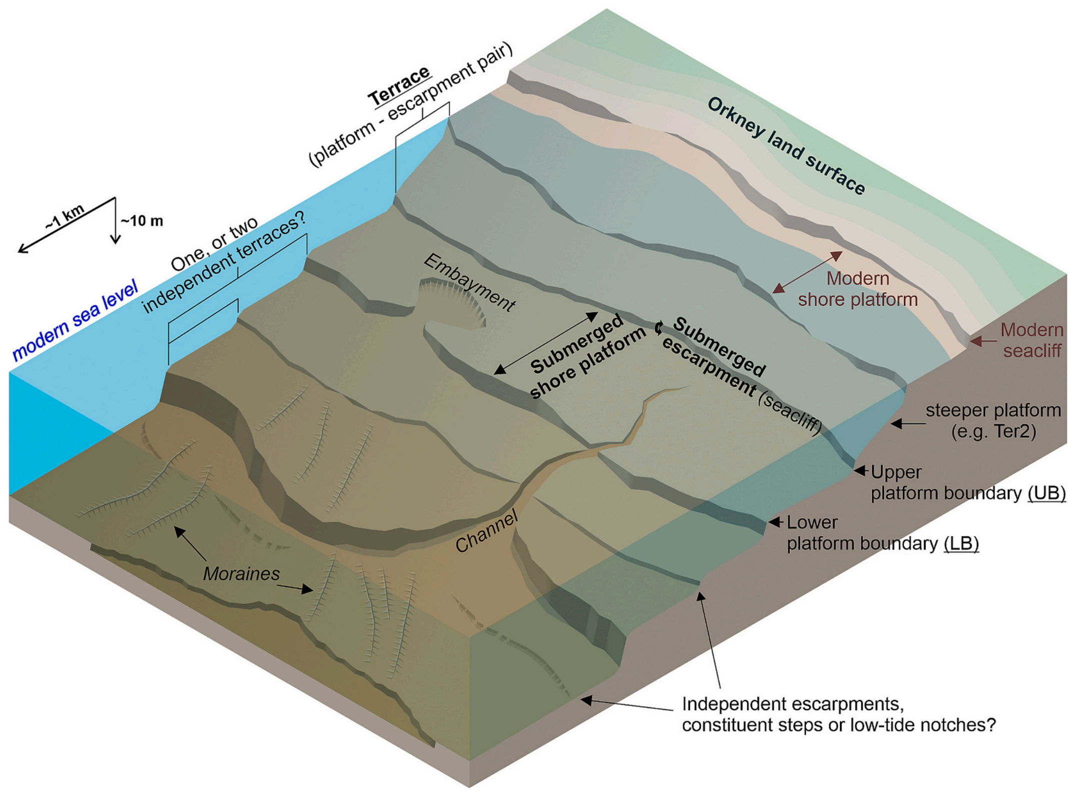

Fig. 9. Conceptual 3D Diagram displaying key elements of the shore platform sequence, observed and mapped, offshore Orkney.

highest relief lower-bounding escarpment (up to ~20 high) in the whole sequence (Figs. 2–5). The conspicuous bedrock platform north of North Ronaldsay in 48–50 m water depth has a dense and clearly visible fracture pattern largely devoid of sediment cover. Here the platform is effectively horizontal over large areas from its landward to seaward boundaries, even having a slight reverse-slope morphology in places. Within the eastern sequence, Terrace 8 is also incised by several channels that also cut into Terraces 5–7.

4.2.9. Terrace 9: -57 m (UB) to -58 m (LB)

A minor, low-relief, platform seen in multiple locations around Orkney (Figs. 2–5). It is identified and correlated primarily due to its relative position below prominent Terrace 8 (with which its formation may be related), and its narrow water depth range.

4.2.10. Terrace 10: -57 m (UB) to -62 m (LB)

Another minor bedrock terrace, but the deepest observed in the eastern Orkney sequence where basin-filling sediments cover any potential deeper terraces (seaward) (Figs. 2–5). This terrace may be related to the formation of Terraces 8 and 9 (see above), and overlaps slightly in its depth range.

4.2.11. Terrace 11: -65 m (UB) to -68 m (LB)

Another relatively minor, low relief and low width, terrace observed exclusively to the northeast of Orkney (Figs. 2,4,5). No channels have been confidently mapped (i.e. distinguished from fractures) in the surface of Terrace 10, Terrace 11 or the lower elevation terraces. Terrace 11 may be related to the development of Terrace 12 or 13 (see below).

4.2.12. Terrace 12: -73 m (UB) to -76 m (LB)

A low-relief terrace, like Terrace 11, it appears to be a minor constituent of the extensive platform in the far northeast between Terrace 8 (LB) and Terrace 13 (LB) (Figs. 2,4,5). Due to the relatively low relief of its lower escarpment (~3 m), Terrace 12 may be associated with the formation of Terrace 13 at a similar elevation (see below).

4.2.13. Terrace 13: -78 m (UB) to -83 m (LB)

A prominent well-developed terrace with a very wide bedrock platform (500 m to greater than 4 km) at around 80 m water depth and high-relief lower escarpment (up to 12 m) (Figs. 2,4,5). Together with Terrace 12 this platform forms an extensive protruding bedrock 'step' to the north of the Orkney Islands. Lower-resolution regional bathymetry data (EMODnet Digital Bathymetry, 2022) suggest Terrace 13 persists further north towards Shetland. The full extent of Terrace 13 cannot be mapped with the currently available MBES data coverage.

4.2.14. Terrace 14: -92 m (UB) to > -93 m (undefined)

Terrace 14 is the lowest submerged platform mapped (Fig. 4). Only the (UB) is observed at the base of the prominent escarpment fronting Terrace 13, hence why not labelled on Figs. 2 and 5. However, available MBES data and regional EMODnet bathymetry suggest that the seabed below this depth (~95 m) does not exhibit the clear, planar, stepped morphology of the shallower platforms seen around Orkney.

4.3. Terrace depth and width

To assess the depth distribution of the submerged terraces we extracted the depth below mean sea level from i) both the mapped UB and LB lines, as well as ii) a histogram plot of the of the bathymetry data (independent of potential interpretation bias) (Fig. 6). This demonstrates the general stepped configuration of the terraces and clustering of data (i.e. elevation values concentrated around platforms), but also shows overlap between the depths of the mapped platforms across the study area. Independent histogram analysis (after Passaro et al., 2011) also suggests a good fit with several of the more pronounced mapped terraces:

- Approx. -34 m to -40 m, apparent correlation with mapped terraces 5 and/or 6;
- Approx. -48 m to -56 m, apparent correlation with mapped terraces 8, and potentially 9;
- Approx. -67 m to -75 m, apparent correlation with mapped terraces 11 and 12;
- Approx. -79 m to -83 m, apparent correlation with mapped terrace 13.

We have also calculated platform width for the terraces around Orkney by measuring perpendicular distances between the lower boundaries (L. B.) (i.e. convex break in slope) of adjacent platforms (Fig. 8). This assessment is broadly consistent with our analysis of platform depths. Notably, that the most prominent terraces (Terraces 6, 8, and 13) exhibit particularly high widths: approximately 1100 m, 2500 m, and 2800 m, respectively.

4.4. Moraines and channels - relationship with submerged terraces

We map several channels and glacial moraines incising or superimposed upon the submerged terraces (Figs. 3, 5, 9). The channels (commonly 2-4 m deep, 20-60 m wide) cut into bedrock are mostly oriented approximately perpendicular to modern coastlines and are tentatively interpreted to have formed as post-glacial fluvial channels (i.e., palaeochannels). The presence of these landforms indicates that terrace development pre-dates channel and moraine formation where they overlap. These observations are useful indicators of terrace formation and relative chronology.

A number of channels are observed on Terraces 5–8 (east and west of Orkney), and other, less clear, channels are observed incising Terraces 8–12 in the north. Numerous recessional moraines (commonly 1–3 m high, 50-150 m wide) (e.g., Bradwell et al., 2021) are preserved atop Terraces 11–13 in the northern part of the study area, and in water depths >100 m (i.e. below terrace 13). Moraines are observed atop Terrace 8 in the southwest of the study area, where this terrace is quite narrow. Moraines are notably absent where Terrace 8 is prominent in the north, however this may result from high exposure to erosive wave and tidal forces in this geographic position. Within inter-island areas, moraines are preserved at depths equivalent to Terrace 8, however no clear platform morphology is observed here.

5. Discussion

5.1. Formation model for Orkney's submerged bedrock terraces

There are several potential explanations for the mode of formation of the observed submerged bedrock terraces offshore Orkney: i) antecedent bedrock features, ii) glacial erosion, iii) modern hydrodynamics, or iii) submerged former shore platforms. Here we consider each model in turn and assess how well they accord with the accumulated evidence.

5.1.1. Antecedent bedrock features

One hypothesis is that the submerged terraces are the expression of bedrock structures, and simply reflect preferential weathering of the regional bedrock preserved at the seabed. We find that this is unlikely as the terrace morphology, consisting of platforms and escarpments, cannot be explained by prevailing bedding planes and fracture patterns alone (Utley et al., 2023). Further to this, bedrock structures (folds, faults, exposed strata) can be clearly seen independent of terrace morphology (e.g. Figs. 3,4). No faulting is observed to offset terraces, and many large-scale fractures run continuously through multiple terraces, indicating no strong geological control. Also, while the tectonic regime accounts for the NE-SW trending Orkney-Shetland platform, and the broader bedrock edifice (Schiffer et al., 2020), an antecedent bedrock origin cannot explain the clear coast-mimicking configuration of the terraces.

5.1.2. Glaciation

Erosive glacial processes can generate distinctive indented coastal geomorphology (e.g. troughs, deep bays, fjords). However, whilst ice-sheet glaciation has significant erosive potential (over millennia) (Benn and Evans, 2014), and is known to have impacted this region multiple times during the Quaternary (e.g. Hall and Hansom, 2021; Bradwell et al., 2021; Newton et al., 2024), we cannot identify a glacial process that could form a series of distinct sub-horizontal terraces in bedrock, particularly as the terraces exhibit irregular planform outlines that mimic the modern coast.

5.1.3. Modern hydrodynamics

The modern hydrodynamic environment around Orkney is highly energetic (Neill et al., 2017) with relatively high seabed-shear stresses predicted (Wilson et al., 2018). We cannot identify a viable mechanism in which oceanographic (tidal and wave) forcings could generate the observed seabed morphology at depth without major fluctuations in RSL nor are we aware of any global examples of hydrodynamically generated >km-wide bedrock terraces in subtidal settings. Also, the depths of most terraces identified here are below the depth of modern wave base.

5.1.4. Shore platforms (preferred model)

Modern, or active shore platforms are sub-horizontal to gently sloping rock surfaces that generally form around the elevation of mean sea level (MSL) by a combination of physical, biological, and chemical weathering and coastal (or shallow marine) erosion (Sunamura, 1992; Trenhaile, 2000, 2002; Kennedy et al., 2014; Poate et al., 2018; Lebrec et al., 2022). The inner (landward) margin of shore platforms (i.e. cliff-platform junction) typically occurs between MSL and mean high-water springs (MHWS), with the outer platform margins commonly between mean low-water springs (MLWS) and local storm wave base-level, below which mechanical abrasion is reduced (Sunamura, 1992; Kennedy et al., 2014). Shore (or wave-cut) platforms are common along energetic rocky coasts and are currently found around the British Isles coastline, including Orkney, within the modern-day tidal range (Moses, 2014; Hall and Hansom, 2021). Most bedrock shore platforms are mechanistically linked to landward coastal erosion resulting in sea cliff/escarpment development (Trenhaile, 2002; Tsuguo, 2018), together forming a terrace morphology (i.e. platform-escarpment pair).

Based on the accumulated geological and geomorphological evidence, we interpret the submerged bedrock terraces around the Orkney Islands as an exceptional sequence of palaeo shore-platforms (or *wave-cut platforms)*, formed in response to periodic changes in RSL. Previous workers who identified 1 or 2 submerged rock platforms around Shetland and Orkney, proposed a similar *intertidal marine erosion* hypothesis for their formation (Flinn, 1964, 1969; Smith et al., 2019). Interestingly, and emphasising the potential significance of the Orkney submerged terraces, there have been notably few reports of such features in areas impacted by former glaciation and the effects of glacial isostasy on RSL (such as around the British Isles and NW Europe). Isostasy introduces further complexity in attempts to decipher the evolution and age of these features, and likely also impacts their preservation potential (discussed further in 5.3). Submerged or drowned (subtidal) rock platforms have previously been identified in a small number of locations around Scotland, although mapping quality varies. Most were mapped prior to the advent of high-resolution echosounder bathymetry data using only coarse bathymetric contours or 2-D seismic reflection data. However, this limited number of previous studies indicates that the submerged platforms offshore the east coast of Scotland (Stoker and Graham, 1985) and around Orkney and Shetland (Flinn, 1969, Flinn, 1977) are unusually wide (500–2000 m) and well developed compared to those seen onshore. Adrian Hall (in Smith et al., 2019) relates their exceptional width to three factors: (i) lower resistance of weaker Devonian and Permo-Triassic sedimentary rocks in the eastern NSB; (ii) the long duration of RSL lowstands in the Middle and Late Pleistocene, and (iii) possible intense frost action during (unglaciated) cold intervals.

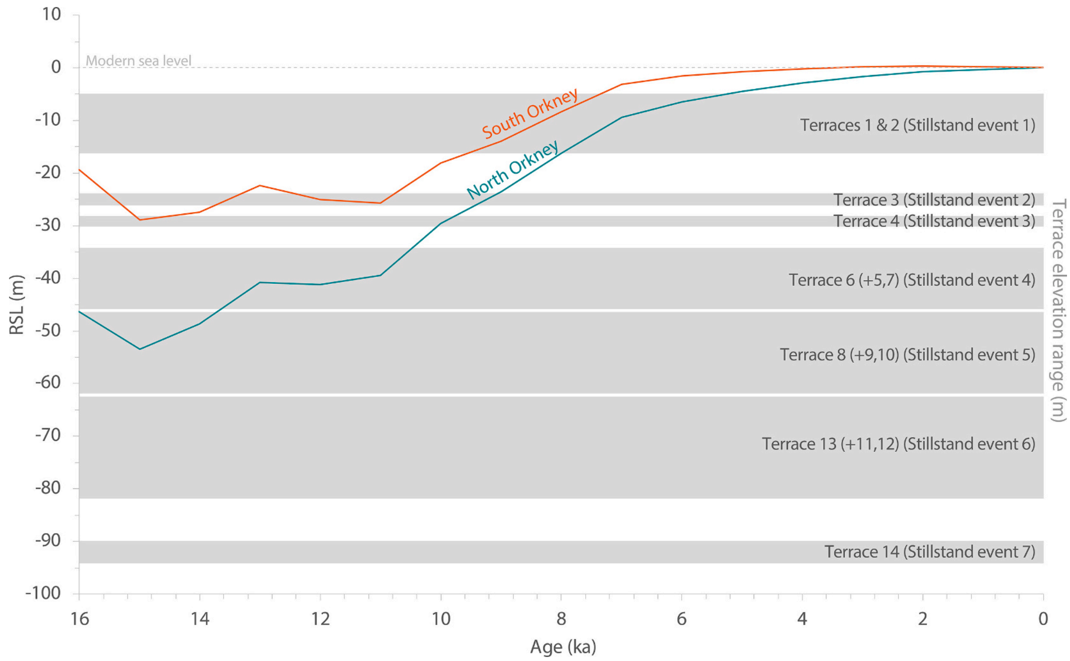

Fig. 10. Relative sea level (RSL) modelled for southern and northern Orkney, by PALTIDE (Scourse et al., 2024; Bradley et al., 2011) from 16 ka to present. Elevation ranges of the documented submerged terraces (grouped by proposed stillstand event, from Table 1) are plotted in grey bands. Stillstand event numbering does not necessarily relate to a specific temporal order of formation, and potential correlation to the modelled RSL variation is highly tentative, and presented to support discussion around candidate chronologies.

Further submerged shore platforms have been observed in Norway (Lebesbye and Vorren, 1996), and RSL low-stand deposits are also observed offshore Ireland (Kelley et al., 2006). A Pleistocene origin (at least in-part) is ascribed for each of these NW European occurrences, either via absolute dating techniques (Lebesbye and Vorren, 1996; Kelley et al., 2006) or by relative association (Sutherland, 1984; Stoker and Graham, 1985; Flinn, 1969, 1973). Our new findings from Orkney confirm and considerably extend the inventory of shore platforms reported in formerly glaciated regions.

Similar landform sequences to those mapped in Orkney (i.e. multiple, stepped, shore platforms) have been described in lower-latitudes in both terrestrial and submarine settings, and are sometimes synonymously referred to as *marine terraces* (e.g. Pedoja et al., 2014; Ricchi et al., 2018; Lebrec et al., 2022). Rovere et al. (2016), however, distinguish shore platforms and marine terraces as separate landforms. They characterise shore platforms as having exposed rock surfaces, and exhibiting platform widths of 10s to 100 s of metres, whereas marine terraces generally have wider dimensions (100 s metres to kilometres) and are typically covered by coastal and/or marine sediments. Importantly though, we note that Rovere et al. (2016) also describe both features as forming through similar mechanisms, centred upon MSL. Within this study, and consistent with previous literature (e.g. Smith et al., 2019; Hall and Hansom, 2021), we use the term ‘shore platform’ because, despite the Orkney features reaching several kilometres in width, they are likely formed in bedrock exposed at the seabed. The descending stepped sequence of shore platforms results in a terraced seabed morphology, and we refer to the combined landform assemblage as a ‘shore-platform sequence’.

Two other lines of evidence support our preferred shore-platform formation model: their distribution and 3D form. As described earlier, well-developed shore platforms currently exist along Orkney’s modern coast at, or close to, present-day sea level (e.g. Smith et al., 2019; Hall and Hansom, 2021), with the region’s highly-energetic wave and tidal regime impacting on Orkney’s rocky coast (Hashemi et al., 2015). Fig. 7 plots platform depth (L.B.) against latitude, demonstrating that platform depths generally increase to the north (except platforms 11–13 which occur over a very narrow latitudinal window). This is consistent with modelled RSL (Scourse et al., 2024) that predicts lower RSL (Fig. 10) during the Post-glacial period in the north of Orkney than the south due to the spatial variable isostatic response to the palaeo ice load over Scotland (Bradley et al., 2011; Clark et al., 2022), again supporting the hypothesis that these features have a relationship with RSL. The Orkney submerged terraces are generally coast-parallel, giving the impression that they are natural extensions of the present-day bedrock coastline. The rock platforms dip gently seaward at low angles, similar to present-day shore platforms; and are bounded by steeper slopes/escarpments, resembling relict cliff lines. We find that the Orkney bedrock terraces exhibit platform and escarpment dimensions (height, width, slope, etc) generally consistent with the range of modern and relict shore platforms observed elsewhere (e.g., Kennedy et al., 2014).

Taken together, we propose that Orkney’s submerged individual bedrock terraces were formed in palaeo-coastal zones during periods of RSL ‘stillstands’, where platform elevations equate to mean sea levels over periods of many years (centuries to millennia), depending on the rate of erosion (discussed further below). One caveat is that several minor terraces (e.g., Terraces 7, 9, 10, 11) may be constituent parts of more prominent adjacent terraces in the sequence (Section 5.3; Figs. 3–5,9). Extensive shore platform development was likely linked to contemporaneous landward coastline erosion and cliff formation, as observed on modern coasts (Swirad et al., 2020 and references therein). This landform pair (i.e. the shore platform and accompanying cliff/escarpment) morphologically constitutes a ‘terrace’ and probably represents a single sea-level stillstand event of sustained duration. This model is consistent with that of shore platform development elsewhere, such as Australia (Brooke et al., 2017), the Azores (Ricchi et al., 2018), California (Laws et al., 2020).

5.2. *Platform dimensions and rates of erosion*

Shore platform width is a useful metric to help understand the development and evolution of shore-platforms. Platform widths are known to vary from site to site, influenced by variable rock properties, seabed gradients, and related tidal and wave regimes (Kennedy, 2015). Determining platform erosion rates and linking shore platform development to specific sea-level events is a subject of significant ongoing research (Trenhaile, 2018, 2019; Swirad et al., 2020). Malatesta et al. (2022) demonstrate that sea-level highstands are not necessarily required for platform development, but rather the duration of a sea-level 'stillstand' is key, meaning the history of regional RSL change, rather than the timing of maximum barystatic sea level, is key. By way of example, Trenhaile (2001) demonstrated that greater platform widths formed during longer highstand events than in glacial times.

With broadly uniform rock properties (i.e. predominantly Devonian sedimentary rocks) expected offshore Orkney (Mykura, 1976; British Geological Survey, 1985), we interpret that wider platforms, and higher-relief landward cliff/escarpments (e.g. Terraces 6, 8, and 13), are likely attributable to longer RSL stillstand events, with the caveat that localised variations in rock properties and potentially variable hydrodynamic regimes between different stillstand events may also influence ultimate platform width. In rocks of potentially similar erosion susceptibility to those found offshore Orkney (e.g. mudstones, siltstones, red sandstones), Moses (2014), Stephenson et al. (2019), and Trenhaile and Porter (2018) estimate down-wearing rates of 0.03–25 mm/year, 0.5–1.2 mm/year, and 0.2-2 mm/year for these rock types, respectively. Applying these values to simply calculate erosive down-wearing of 2–20 m (i.e. range of observed escarpment relief offshore Orkney; ignoring any ongoing uplift/subsidence), RSL stillstand events of between approximately 1000 and 20,000 years would be required. However, more detailed work is clearly needed to reduce the uncertainties of this first-order analysis; in particular, assessing contemporary inter-tidal rock removal rates on Orkney and exploring the impact of bedrock heterogeneity on marine erosion rates.

Table 1
Summary of mapped terraces (i.e. platform / escarpment pair) indicating their interpreted grouping, and potential link to individual RSL stillstand events. Stillstand event numbering is given for simplicity, but does not necessarily relate to a specific temporal order of formation.

RSL stillstand event (*Note: Does not infer temporal formation order)*	Mapped Terrace ID	Terrace feature description (s) and *qualitative confidence*	Depth range (m MSL) (LAT)
1?	Terrace 2, including Terrace 1	Distinct terrace, but with less clear platform morphology than lower terraces; *Low-medium* confidence it formed during a single stillstand (potentially associated with terrace 1 which lacks clear morphology)	-5 to -16
2	Terrace 3	Distinct terrace; *Medium confidence* it formed during a single sea-level stillstand.	-24 to -26
3	Terrace 4	Distinct terrace; *Medium confidence* it formed during a single sea-level stillstand.	-28 to -30
4	Terrace 6, including Terraces 5 & 7	Extensive and pronounced terrace; *Medium-high confidence* it probably incorporates terraces 5 and 7 as constituent parts (i.e., steps, and/or low-tide notches) and together represent one stillstand.	-34 to -46
5	Terrace 8, including Terraces 9 & 10	Extensive and pronounced terrace; *High confidence* it probably incorporates terraces 9 and 10 as constituent parts (i.e., low-tide notch(s)) and together represent one stillstand.	-46 to -62
6	Terrace 13, including Terrace 11 & 12	Extensive and pronounced terrace; *High confidence* it probably incorporates terraces 11 and 12 as constituent parts (i.e. steps) and together represent one stillstand.	-62 to -82
7?	Terrace 14	Limited mapping, however, bathymetry data and depth histography indicate a potentially prominent platform; *Low confidence* in formation due to lack of data	-90 to -94

5.3. Terrace forming episodes and relative event chronology

Although we are confident in ascribing a shore platform origin for Orkney's submerged terraces, determining the number of terrace-forming episodes is challenging owing to their erosional nature and possible inheritance from previous sea-level (or glacial-interglacial) cycles (Trenhaile, 2002; Kennedy et al., 2014). In line with models of shore-platform formation discussed above, each landform pair (i.e. shore platform and landward cliff/escarpment) can be generated during a single RSL stillstand (e.g. Trenhaile, 2002, Kennedy et al., 2014; Ricchi et al., 2018). As 12 distinct terraces (Terraces 2–13) have been mapped, a maximum of 12 separate stillstand episodes may be inferred. However, due to the reasons outlined below, we suggest that fewer RSL stillstand events are probably recorded offshore Orkney.

As previously described (see Section 4.4) and observed in Figs. 3–5, several terraces (7, 9–12) are relatively minor features, with low relief (commonly <1 m) and may only represent constituent parts of the more prominent neighbouring terraces. Shore platforms are known, at times, to include small steps resulting from variable lithology or structural heterogeneities (Moses, 2014), making these minor terraces simply a component of the wider platform. The tidal range is also known to significantly influence shore-platform morphology, with sloping platforms and sub-horizontal platforms representing end members (Sunamura, 1992; Rovere et al., 2016). Sub-horizontal platforms (with slopes less than 1°) typically occur within microtidal to mesotidal environments and commonly comprise a low-tide cliff (or 'notch') at the seaward terminus of the platform (Kennedy, 2016). If reduced tidal ranges prevailed during the formation of any of the Orkney terraces, some of the mapped escarpments may instead be low-tide cliffs (Sunamura, 1992). In this scenario, where two terraces are mapped with similar elevations (for example, 6 & 7 or 8 & 9), the lower-elevation terrace probably represents a low-tide cliff associated with the more prominent higher-elevation terrace. This phenomenon may partially account for the close stepped configuration of terraces to the east of Orkney. Therefore, considering the combined evidence (mapped terrace depths and independent histogram analysis), we estimate 5–7, notable RSL stillstands are likely recorded in the shore-platform sequence (Table 1).

This study is based on analysis of high-resolution bathymetry but currently there is no data available to determine the absolute chronology of the shore-platform sequence. Despite this limitation, it is still possible to assess the potential order of terrace formation, and scenarios of relative event chronology.

One hypothesis is that the terraces formed in sequential order, with the deepest terraces forming first, and the shallowest most recently. Under this scenario, each terrace (or shore platform and associated cliff) must have formed at or near MSL and progressively subsided to its current depth range due to long-term RSL rise, for example, caused by tectonic subsidence. By way of example, the inverse phenomenon is observed on marine terraces now sub-aerially exposed in California due to progressive tectonic uplift (e.g. Pedoja et al., 2014; Simms et al., 2020) and around central Scotland due to isostatic rebound following deglaciation (Smith et al., 2024).

An alternative hypothesis is that the terraces were formed out of elevation sequence; i.e. their present-day water depth does not necessarily signify relative age. In this scenario, the terraces would have formed at or near MSL, but subsequent changes in RSL (either rising and/or falling) would result in the depth order of the terraces being different from the order in which they formed. This is possible owing to the complex RSL history of the region, but would imply that several terraces have survived RSL change during one or more glacial-interglacial cycles (e.g., Siddall et al., 2007). This scenario allows for the prospect that, following initial formation, some terraces may have been subaerially exposed during periods of lower RSL. Apparent palaeochannel incision through several of the terraces (e.g. Terraces 5–7) supports this hypothesis, as well as the relict embayments and coastline-mimicking morphology of Terraces 3–6. Out-of-sequence marine terraces are observed in the Azores (Ricchi et al., 2018), resulting from the interplay between RSL changes and volcano-tectonic processes. Considering the complex interplay between the solid Earth response to ice-load changes, barystatic sea level and dynamic topography along the NW European margin during the Quaternary (Austermann et al., 2017; Barnett et al., 2023; Bradley et al., 2023; Pollard et al., 2024), or even potential regional uplift during the late Miocene or Pliocene (Anell et al., 2009), the interplay of one or more mechanisms could explain the Orkney shore platforms being preserved at elevations that are not in age-elevation sequence.

Further geomorphological evidence gives added relative-age constraints on the evolution of the terraces. Moraines, interpreted to have formed during the last glacial period (Bradwell et al., 2021) are preserved atop Terrace 8 (equivocal, in places), and Terraces 11–13 (unequivocal), indicating that these terraces at least formed *prior to the last glaciation* (MIS 2) (i.e. >30 ka BP). Furthermore, the depths of Terraces 11–13 (>60 m) exceed the minimum modelled RSL elevation following the last deglaciation (Fig. 10) (Scourse et al., 2024; Bradley et al., 2011). In shallower water, Terraces 2 and 3 exhibit a smoother (less rugose), less weathered, bedrock morphology suggesting more recent terrace formation than those at greater depth (i.e. less time and less likely to have been sub-aerially exposed). We surmise that these shallowest terraces, with elevations ranging -5 to -15 m (Terraces 1 & 2) and -24 to -26 m (Terrace 3) are probably the youngest, at elevations within the range of modelled RSL following the most recent deglaciation (including Terrace 4) (Scourse et al., 2024; Bradley et al., 2011) (see Fig. 10).

Below Terrace 4, Terraces 5, 6 and 7 are recorded over an elevation range of -34 to -46 m. Fig. 10 suggests that around 13–11 ka, RSL in northern Orkney was relatively stable at ca. -40 m, tempting age-elevation correlation with the terraces at these depths. However, the presence of palaeochannel forms on Terraces 5–12 leads us to suggest that these terraces must have experienced some form of subsequent terrestrial exposure that is not explained by the (post-LGM) deglacial RSL curves (Fig. 10). This evidence considered together with extensive platform widths and high escarpments of terraces 6 (5&7), 8, and 13 (11&12) suggest that they almost certainly pre-date ~16 ka.

The spatially variable ice history during the late Pleistocene glaciations of Orkney and the Scottish mainland drives spatially variable GIA, potentially leading to complex coastal response to RSL changes (e.g., Matsumoto et al., 2024). Furthermore, though it may be tempting to suggest an age-elevation correlation with stillstands or lowstands present in global sea-level curves (Lisiecki and Raymo, 2005), Fig. 10 demonstrates the importance of not making global correlations in a location where RSL is spatially and temporally complex over short (10s km) distances, and where the trend of RSL is dependent on regional and local ice histories during and following each glaciation.

Based on the accumulated evidence, it seems reasonable to tentatively suggest that at least some of the Orkney shore-platform sequence formed during the Middle-Late Pleistocene, similar to those observed elsewhere offshore Scotland (Stoker and Graham, 1985), Ireland (Kelley et al., 2006), and Norway (Lebesbye and Vorren, 1996). However, due to their erosional nature, it is worth stating that Pre-Quaternary formation of these shore platforms cannot be ruled out – with apparent regional uplift during the Miocene also providing a potential mechanism (e.g., Anell et al., 2009; Hall et al., 2015).

6. Conclusions

A descending sequence of relict shore platforms (and affiliated escarpments) exposed at seabed offshore Orkney are interpreted to record multiple episodes (probably 5–7) of lower relative sea level (RSL) around northern Scotland and in the northern North Sea Basin. This newly mapped shore-platform sequence around Orkney has the potential to provide an important dataset for constraining British and European ice-sheet history and provide motivation for similar work at other locations. Glacial-isostatic adjustment modelling of post-LGM sea-level change around the British Isles has highlighted numerous locations at which RSL would have been significantly below present, but for which there is no constraining geological evidence. This presents significant uncertainty regarding the elevation of former RSL and results in highly varied model outputs, which cannot be tuned to regional ice-sheet histories and isostatic response.

With elevations ranging from -5 to -95 m below mean sea level, we tentatively propose that the Orkney terraces probably represent a range of Mid-Late Pleistocene RSL stillstands, although some of the uppermost shore platforms may have formed – or at least been re-occupied by sea-level – following ice-sheet deglaciation in MIS 2. Acknowledging the multiple and varied uncertainties, we cannot rule out an earlier origin for these shore platforms – with Pliocene or even Miocene formation as potential candidates. Considering the complex RSL history of the region, some of the platforms may have also formed out of elevation sequence.

Advances in bathymetric data resolution and ever-increasing data coverage has allowed us to address the current data shortfall in lower-than-present sea levels, particularly relevant for regions impacted by glacial isostasy. Orkney's submerged shore platform sequence provides a calibration dataset and presents a series of hypotheses to test in future geophysical (Earth rheology) and ice-sheet models. Despite the current absence of chronological constraints, we believe our findings provide valuable information for constraining Earth-system response to ice-sheet volume changes and for understanding long-term RSL changes. In situ dating of the terraces may be possible in the future (though challenging), or ages may be inferred via correlation from the adjacent North Sea basin (e.g. integrating 3D seismic architecture and dated boreholes). In addition, this work provides potentially useful insights on early human migration, bedrock-coastal evolution, and the pre-glacial palaeo-geography of the wider region.

CRediT authorship contribution statement

Dayton Dove: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tom Bradwell:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis. **Natasha L.M. Barlow:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The high-resolution bathymetry data used within this study are publicly available via the Admiralty Marine Data Portal (https://data.admiralty.co.uk/portal/apps/sites/#/marine-data-portal/pages/seabed-mapping-services). Further data used to inform interpretations can be viewed via the BGS Offshore Geoindex (https://www.bgs.ac.uk/map-viewers/geoindex-offshore/).

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