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Is Recent Sea-Level Rise Accelerating? Testing The Theory In Scotland

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1: INTRODUCTION:

During the mid-late Holocene large sections of the Scottish coastline have been characterized by falling relative sea-levels resulting from differential isostatic uplift of this area of northern Britain. The complex interplay between crustal and sea-level movements continues to influence the morphological development of the Scottish. A number of geophysical models predict ongoing uplift of the Scotish landmass (e.g.Lambeck, 1993b; Peltier et al., 2002; Shennan and Horton, 2002; Shennan et al., 2006) and recently published preliminary GPS measurements (e.g. Milne et al., 2006; Terferle et al., 2006). However, these are poorly constrained for the late Holocene and data relating to present day sea-level movements for much of the Scottish coastline is sparse.

Recent studies have suggested that global sea level has been rising at around 1 mm yr^{-1} over the last Century and at an accelerating rate over the last decade or so (e.g. Pethick 1999, 4.0mm yr^{-1} to 2050AD). This view is being tested through existing and ongoing work at a number of locations around the Scottish coastline by investigating the records of sediment accumulation in coastal marsh environments. It is generally accepted that stable mature marsh environments keep pace with rising sea-levels if there is sufficient sediment supply to fill the available accommodation space (Pethick, 1991; Allen, 1990; French, 1993, 1996; Allen, 2000). Measurement of sediment accretion in such settings can therefore be used as a proxy for the assessment of recent rates of sea level rise. This is particularly useful for regions that lack long-term tidal gauge data.

Radiometric dating methods have been widely used to establish chronological models of coastal marsh development (e.g. Cundy and Croudace 1996; Callaway, 1998(b); Thompson et al., 2001) and these provide a robust method of assessing historical rates of sediment accretion within mature marsh environments.

This research focuses upon the recent evolution of inter-tidal coastal marshes along two transects across sections of the Scottish coast. The first of these is situated within the Argyll region of the Western Highlands, where maximum rates of continued crustal uplift are predicted (e.g. <1.2 mm yr^{-1}, Shennan et al., 2002; Figure 1) extending from western Isle of Mull to Loch Etive situated in mainland Argyll . The second transect is situated in the Northeast of Scotland, extending south-west across the Moray Firth from the margin of the Scottish glacio-isostatic uplift centre (e.g. Wick/Bettyhill) towards its centre (Beauly Firth).

The study utilises established radiometric dating methods using the naturally occurring radionuclide ^{210}Pb and the anthropogenic radionuclide ^{137}Cs. The half-lives ^{210}Pb ($t_{1/2}$ = 22.26 years) and ^{137}Cs ($t_{1/2}$ = 30.2 years) renders them both highly suitable for the study of historical marsh sediment accumulation over the last ~120 years. Analysis of the measured down-core activity profiles of these radionuclides provides an opportunity to investigate the linkages between contemporary marsh development and current geodynamics and recent sea-level movements in Scotland. This methodology is supported by Diatom analysis of the marsh cores to further assess the relationship between marsh maturity/stability and recent sea-level movement.

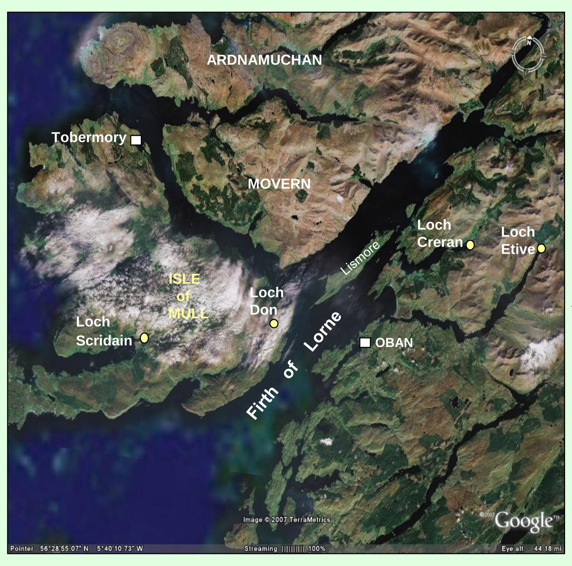
2: THE STUDY SITES: WESTERN SCOTLAND

The four marsh sites investigated in the study are situated on the Isle of Mull, in the west at Loch Scridain and south-east at Loch Don with two other sites situated on mainland Argyll at the heads Loch Creran and Loch Etive respectively (Figure 1).

The sites on mainland Argyll and at Loch Scridain represent areas of marsh situated at the head of some of the major sea-lochs within western Scotland. The marsh at Loch Don represents a semi-enclosed lowland setting surrounded by less mountainous topography, thereby providing a useful contrast in terms of depositional environments.

N.E. SCOTLAND:

Marsh environments at six new sites are currently under investigation. In the north these are situated at Bettyhill and at Wick. Further sites are located to the south-west within the Dornock, Cromarty and Beauly Firths, with an additional site situated within Findhorn Bay east of Inverness (Figure 1).



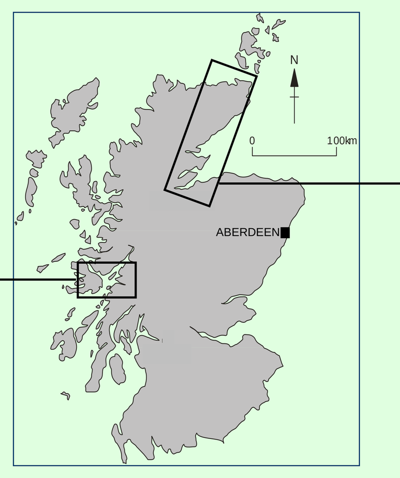


Figure 1: Location of the marsh study sites in Western and North East Scotland.

3: CORE ACQUISITION

Sediment core monoliths were obtained from the respective sites from mature marsh settings.

To ensure that the core samples were from high marsh environments, individual sites were visited over the Spring tide cycle (MHWOST) and potential sampling locations assessed from observation by using surveying ranging poles to mark the position of potential core sites relative to the incoming flood tide.

Observations of this nature proved to be an effective method of establishing the position of sampling sites relative to the tidal frame where distinctive marsh terraces were harder to distinguish.

4: OVERVIEW OF THE ^{210}Pb AND ^{137}Cs DATING METHODS:

^{210}Pb is a naturally occurring radionuclide formed as part of the ^{238}U series decay chain. Dating of coastal sediments is based upon determination of the vertical distribution of unsupported ^{210}Pb ($^{210}Pb_{excess}$) supplied to the marsh surface via wet and dry atmospheric deposition. Ages of sedimentary layers are then calculated based upon the known decay rate of ^{210}Pb. In undisturbed sedimentary systems an approximate exponential decline in $^{210}Pb_{excess}$ activity is normally observed.

^{210}Pb activity was determined using the proxy method of alpha spectrometry measurement of its grand-daughter radionuclide ^{210}Po outlined in Flynn (1966). This method employs acid leaching of the sediment including the addition of ^{209}Po as an isotopic yield tracer followed by auto deposition of the Po isotopes on to polished silver discs. Discs were counted on a Canberra 7401 Alpha Spectrometer for a period of 150 000 s. Errors are typically less than 5%. Average sediment accretion rates can be determined using various models e.g. the 'Simple' model (Robbins,1978; Appleby and Oldfield, 1992), where the average accretion rate is given by the slope of the least squares regression of the natural Log $^{210}Pb_{excess}$ activity plotted against depth. A more comprehensive breakdown of marsh sediment accumulation is routinely obtained using the Constant Rate of Supply (CRS) model which uses inventories of $^{210}Pb_{excess}$ activity to calculate ages for discrete depth horizons (Appleby & Oldfield, 1992). The CRS model is now commonly applied to studies of coastal marsh development (e.g. Cundy and Croudace, 1996).

^{137}Cs is an artificial radionuclide introduced into the environment as a result of atmospheric fallout from nuclear weapons testing, authorized effluent discharges and nuclear accidents.

In the Northern Hemisphere marked maxima in atmospheric deposition of fallout ^{137}Cs occurred in 1958 AD and pre-1963 AD prior to the signing of the Nuclear Test Ban Treaty which effectively ended above-ground detonation of high yield thermo-nuclear weapons. Where detected, atmospherically derived ^{137}Cs resulting from the 1986AD Chernobyl accident provides an additional marker horizon that may be used in conjunction with the pre-1963AD activity maxima to determine sediment accumulation rates in coastal wetlands. Other potential sources of radiocaesium to the Scottish coastal zone are from authorised discharges into the Irish Sea from the BNFL Sellafield facility situated on the Cumbrian coast NW England. Maximum discharges of ^{137}Cs occurred in 1974 (>5000 TBq) and a transit (lag) time of ~ I year into western Scottish coastal waters has been estimated (Livingstone et al., 1982).

Identification of sub-surface peaks in ^{137}Cs activity in accumulating, undisturbed sediments can therefore provide an independent marker horizon with which to test the reliability of accretion rates derived from $^{210}Pb_{excess}$ dating.

In the present study ^{137}Cs activities were measured by gamma spectrometry on two Canberra 35% well-type High-Purity Germanium detectors at the National Oceanography Centre, Southampton, UK. Samples were counted for a minimum of 24 hours and errors are typically less than 4%.

5: RESULTS FROM WESTERN SCOTLAND

$^{210}Pb_{excess}$ activity profiles with r^2 values are shown in Figure 2 with average sedimentation rates for the entire core sequences derived from the 'Simple model' calculations. Inferred oxidation/reduction boundaries within the four cores are also indicated based upon major and trace element down-core profiles for Fe_2O_3, MnO (wt%) and S/Cl and I/Br concentration ratios (ppm, profile data not shown). These data indicate that the measured activity of ^{210}Pb and ^{137}Cs used for dating purposes are contained within the upper oxidised section of the cores, and therefore, their distribution is unlikely to have been affected by post-depositional redox migration.

Measured ^{137}Cs activity within the cores is shown in Figure 4. These profiles highlight a lower peak in ^{137}Cs activity corresponding to the pre-1963AD weapons-test signature which is corroborated in this study by the ^{210}Pb dates derived from the CRS model calculations. A further peak corresponding to atmospheric input derived from the Chernobyl accident is also

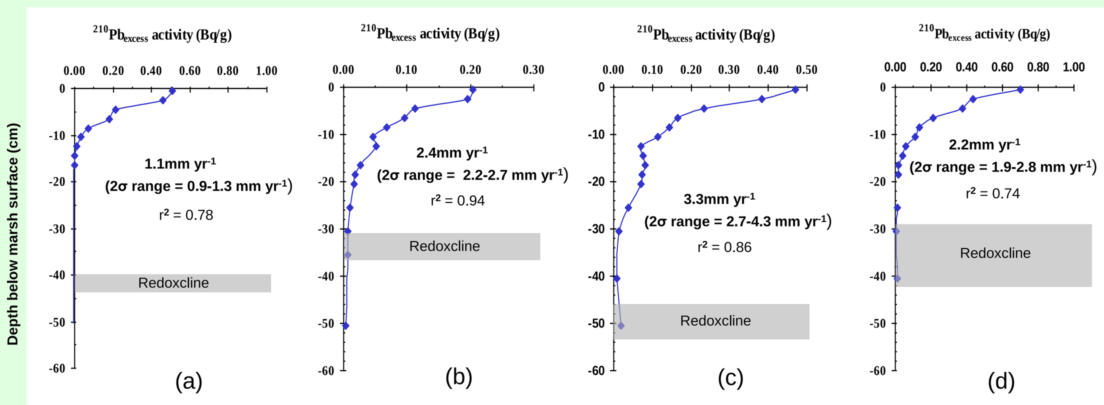


Figure 2: $^{210}Pb_{excess}$ activity profiles for the Argyll marsh cores with average rates of sediment accretion for the last ~ 75 years. (a) Loch Scridain, (b) Loch Don, (c) Loch Creran, (d) Loch Etive.

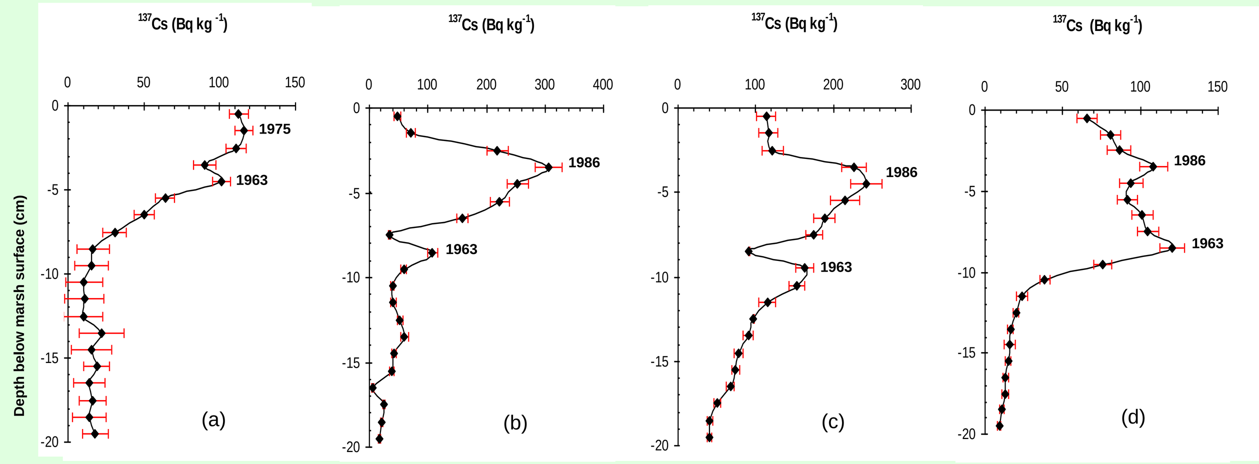


Figure 3: ^{137}Cs activity profiles for the Argyll marsh cores (a-d as for Figure 3).

^{137}Cs derived sedimentation rates (mm yr^{-1})			
Core site	pre-1963 weapons testing	Sellafield	1986 Chenobyl accident
Loch Scridain	1.8	1.1	uncertain
Loch Don	2.3	?	2.5
Loch Creran	2.7	?	3.5
Loch Etive	2.5	?	2.5

Table 1: Sedimentation rates derived from the marker horizons in the ^{137}Cs activity profiles from the Argyll marshes

present in the cores from Loch Don, Loch Creran and Loch Etive. In the core from Loch Scridain the presence of an activity peak relating to the 1986 Chernobyl accident is not discernable and is therefore likely to have been masked by inputs derived from Sellafield discharges. A ^{210}Pb CRS model date of 1975AD for the upper peak in ^{137}Cs activity in this core agrees well with the estimated travel time of approximately one year for maximum Sellafield discharges of ^{137}Cs reaching western Scottish coastal waters (Livingstone et al., 1982). As such this also provides useful marker horizon for assessment of sedimentation rates within this core. Rates of sediment accumulation derived from the ^{137}Cs activity profiles are summarised in Table 1. $^{210}Pb_{excess}$CRS model calculated ages for the cores are presented in Figure 4. These graphs highlight the more subtle variations in the rates of sediment accumulation over shorter time-periods.

In the core from Loch Scridain rates of sediment accretion have been fairly constant through out much of the Twentieth Century (~ 75 years) with an average value of 1.1mm yr^{-1} (Figures 2 & 4). In the cores from Loch Don, Loch Creran and Loch Etive, sedimentation rates have been somewhat higher over the same period of time with values ranging from 1.9- 4.3 mm yr^{-1}.

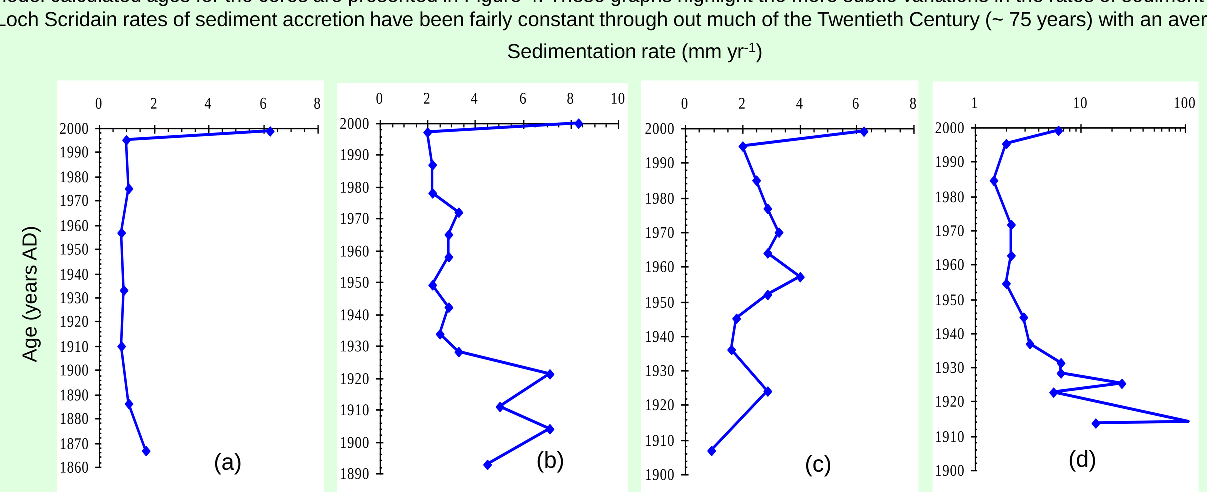


Figure 4: Sedimentation rates derived from the $^{210}Pb_{excess}$ CRS model calculations, (note the significant increases recorded in the near-surface layers of the marsh cores from all four sites.

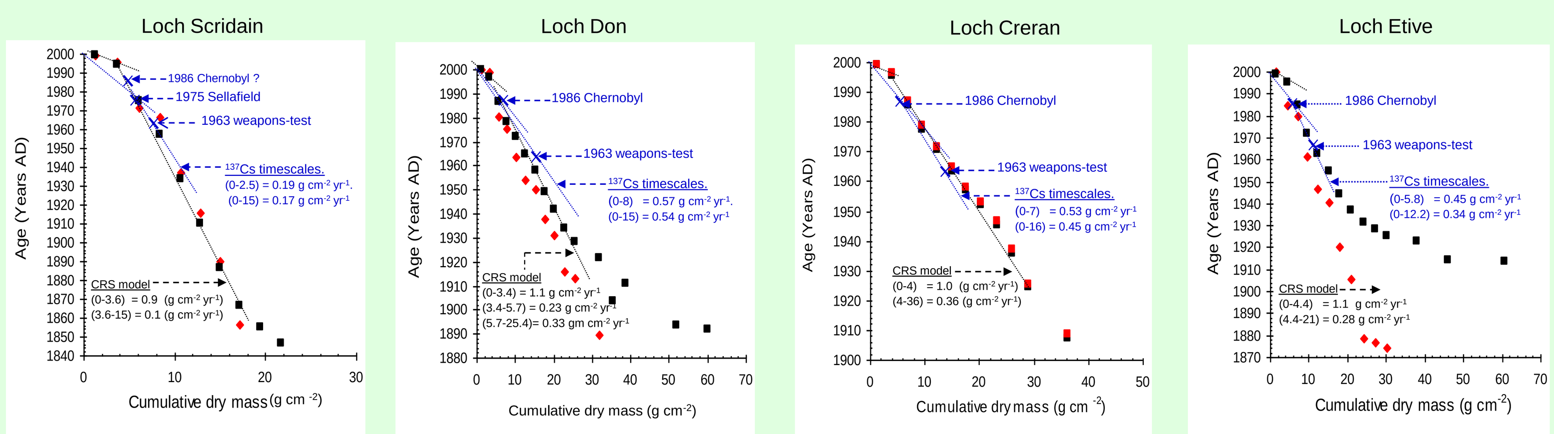


Figure 5: Cumulative mass (g cm^{-2}) versus CIC and CRS model ages (red diamonds & black squares) with ^{137}Cs timescales shown in blue. (note: for clarity only ^{210}Pb CRS model and ^{137}Cs accumulation rates are shown (black and blue trend-lines respectively).

A significant finding highlighted from the CRS model calculations is the very recent increase in marsh sedimentation rates recorded at all four sites in the near-surface sediments (Figure 4). To investigate this further the $^{210}Pb_{excess}$ CRS model ages and ^{137}Cs marker horizons have been plotted against cumulative dry mass of sediment (g cm^{-2}; Figure 5). This effectively removes any effects that may have influenced rates of sedimentation (mm yr^{-1}), e.g. sediment compaction. In all the cores these plots reveal significant increases in deposited sediment dry mass (gm cm^{-2} yr^{-1}) in the near-surface layers, supporting the $^{210}Pb_{excess}$ CRS model rates of sedimentation (mm yr^{-1}) and furthermore indicating that the measured increase in rates of sedimentation at all four sites is not an artefact of the ^{210}Pb dating models.

Further insight into the nature of the apparent increased rates of sedimentation within the marshes can be obtained from the analysis of Diatom assemblage distributions within the cores shown in Figure 6. The cores from Mull and Loch Creran show the uppermost 10cm only, whereas the previously recorded assemblages from Loch Etive shows data for the entire core section.

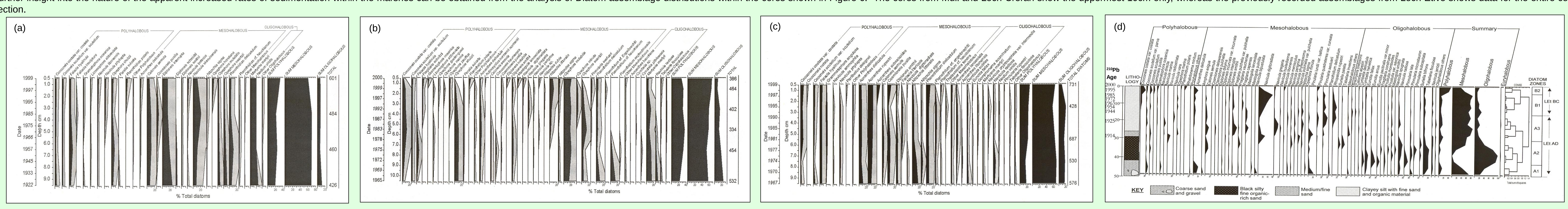


Figure 6: Diatom assemblage summary data from the (Argyll) Western Scotland marsh cores. Frequencies are shown as percentages of the total diatom count with taxa at <1% included in the 'Others' sums for each halobian class. Chronologies are those estimated from the $^{210}Pb_{excess}$ CRS model calculations. a) Loch Scridain, b) Loch Don, c) Loch Creran, d) Loch Etive.

These diagrams indicate that for much of the latter half of the Twentieth Century the marshes have been stable environments supporting the radiometric dating results and major element geochemistry (data not shown here). In the near surface layers of the cores subtle changes in species frequencies (as a percentage of total diatoms) are evident, with key polyhalobian and mesohalobian taxa more indicative of low marsh and mud/sandflat environments being recorded upon the mature marsh surfaces. This data also supports the radiometric dating indicating an increase in new material currently being deposited upon the 'high' marsh environment.

6: WORK IN PROGRESS, N.E SCOTLAND

The work undertaken in western Scotland highlights the recent onset of significant increased rates of sedimentation within the coastal marshes of the Argyll region, Western Scotland. Recent fieldwork has been undertaken in N E Scotland to extend the present study. Marsh cores have been extracted from sites within the Dornock Firth, Cromarty Firth, Beauly Firth and further east within Findhorn Bay and from sites at Bettyhill and Wick (see Figure 1).

Ongoing radiometric dating of cores from these sites is being undertaken to assess rates of marsh sediment accretion and provide detailed geochronological models of marsh evolution from the N.E coastline. Currently, data from the Bettyhill site is available. At this site, on the margin of the Scottish glacio-isostatic uplift dome, recent rates of sedimentation of 5.0 mm yr^{-1} are recorded in the near-surface sediments (Figure 7). Field observations at all the sites indicate that rapid morphological adjustment of marsh areas is currently taking place with the development of relict marsh tussock features prevalent at many sites (Figures 8 & 9). Fringing marsh environments also show evidence of severe erosion. Furthermore, at many locations there appears to be little evidence of low marsh habitat and the modern mudflat surface can now be seen adjacent to eroding high marsh sediments.

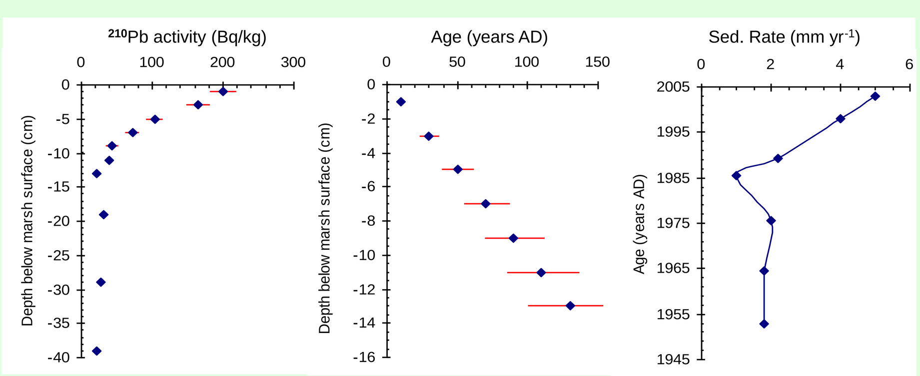


Figure 7: $^{210}Pb_{total}$ activity, CRS model age/depth profile and sedimentation rate vs. age for the Bettyhilll marsh core.

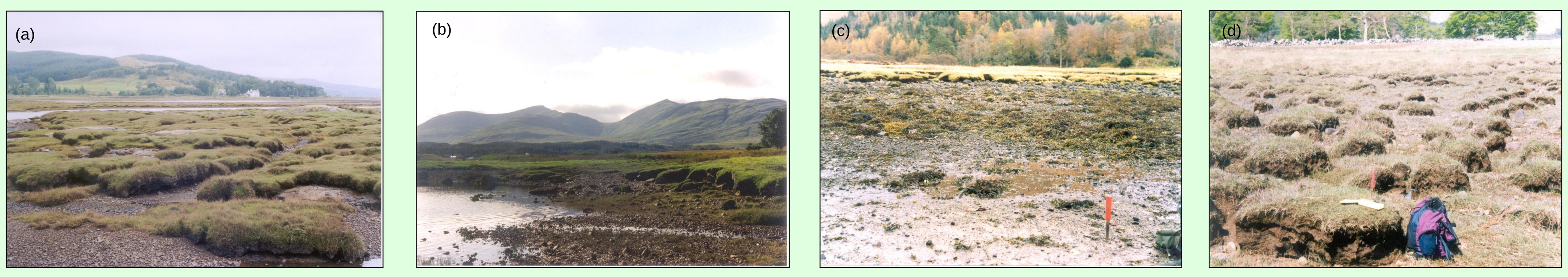


Figure 8: Modern erosion of marshes at the four sites a) Loch Scridain, western Isle of Mull, b) Loch Don south-eastern Isle of Mull, c) Loch Ceran and d) Loch Etive, mainland Argyll.

Detailed discussions with local landowners at sites in Western and N.E. Scotland have further highlighted observational evidence of significant recent retreat of marsh habitat at many sites during the last decade or so where structures such as grazing field walls and conservationally important coastal habitat appear to be threatened by rising sea-level.

7: DISCUSSION and CONCLUSIONS

In the cores from Western Scotland $^{210}Pb_{excess}$ 'Simple' model derived estimates of marsh sedimentation rates provide average values of historical sediment accumulation in the Argyll cores. However, these values are poor estimations of actual sedimentation rates over shorter timescales. A more comprehensive breakdown of sedimentation accumulation is provided by the CRS model calculations (Appleby and Oldfield, 1992). In the core from Loch Scridain rates of sedimentation have been fairly constant throughout much of the 20th Century with values of 0.9-1.3 mm yr^{-1} (2 σ range), in good agreement with estimations from the only long-term tide gauge record situated at Aberdeen on the east coast (1.1. 0.15 mm yr^{-1}, Figure 1). In the cores from Loch Don, Loch Creran and Loch Etive, accumulation rates are somewhat higher with fluctuating values of between 1.9 – 4.3mm yr^{-1} (2 δ range) over the last ~75 years. Periods of sedimentation that exceed the tide gauge data are likely to represent periods of marsh catch-up following periods of reduced sediment supply and is characteristic of more youthful marshes. Indeed comparison with the Loch Scridain core $^{210}Pb_{excess}$ CRS model chronology indicates that the marsh sediments at this site are likely to be significantly older.

^{137}Cs down-core profiles show distinct activity maxima corresponding to know periods of input to the environment from a number of sources. These marker horizons can be tested against the ^{210}Pb derived ages providing an indication of the reliability of the ^{210}Pb method. Good overall agreement is observed between the two models of dating suggesting that ^{210}Pb can be used in similar coastal settings around the Scottish coast .

An important finding of the study are the significant increases in sediment accumulation being recorded within the near-surface layers of the four cores from western Scotland and at the Bettyhill site (Figures 4 & 7), with values ranging from 5-9mm yr^{-1}.

Field evidence indicates that the marshes at all the sites are now undergoing significant morphological adjustment in the form of erosion of present day low marsh and sand/mudflat areas (Figures 8 & 9). This new material is being redistributed and deposited upon the mature marsh sites as these systems readjust to changes in the tidal prism and accommodation space.

Diatom analysis of the cores from Western Scotland supports this view and show subtle increases in the frequency of some polyhalobian and mesohalobian species, more representative of mud/sandflat to low marsh environments, now being deposited on the mature marsh surfaces. It could be argued here that these species are essentially autochthonous taxa which have become allochthonous taxa as a direct result of morphological re-adjustment of marsh habitat. This data also strongly suggests that the source of new material now accumulating on the upper marsh surface is derived from the lower inter-tidal environment.

Current sedimentation rates occurring on the marsh surfaces further indicate that the rate of present-day sea-level rise is now well in excess of the rates for the 20th Century proposed by Shennan and Woodworth (1992, 1.0 0.15mm yr^{-1}) and are also exceeding the more recent estimations of Pethick (1999, ~ 4.0mm yr^{-1} to 2050AD), and the zonal estimations for western Scotland proposed by Dawson et al., (2001) to 2050AD, (<2.9 mm yr^{-1} to < 3.4mm yr^{-1}). These rates of sedimentation are also greater than the recently published satellite altimetry measurements of northern hemisphere sea-level rise (3.1 0.4mm yr^{-1} since 1993) as proposed by Nerem et al., (2006).

Importantly, in terms of present-day geodynamics in western Scotland, the rates of recent sea-level rise are also significantly exceeding estimations of residual crustal uplift predicted by the various geophysical models (e.g. Shennan and Horton, 2002) and recent GPS measurements (e.g. Milne et al., 2006). Furthermore, if these rates of sedimentation do reflect present-day rates of sea-level rise for the region, they are in good agreement with the UK Climate Impacts Programme report estimations (under the IPCC 'high' emissions scenario) for sea-level rise to 2050AD for Scotland (Walmsley et al., 2007; 30cm net sea-level change relative to 1961-1990 taking into account the isostatic uplift model of Shennan and Horton, 2006).

The morphological re-adjustment now taking place within the marsh systems studied provides evidence of a direct response to a very recent increase in coastal forcing in the form of accelerated relative sea-level rise which is now strongly influencing contemporary lowland coastal development around the Scottish coast.

Marsh environments in Scotland will require further monitoring to assess the future morphodynamic response of these inter-tidal sedimentary systems under a scenario of continued rapid regional sea-level rise highlighted by this study. Future management strategies will be required that address the likely future reduction of valuable and ecologically important lowland coastal habitats.

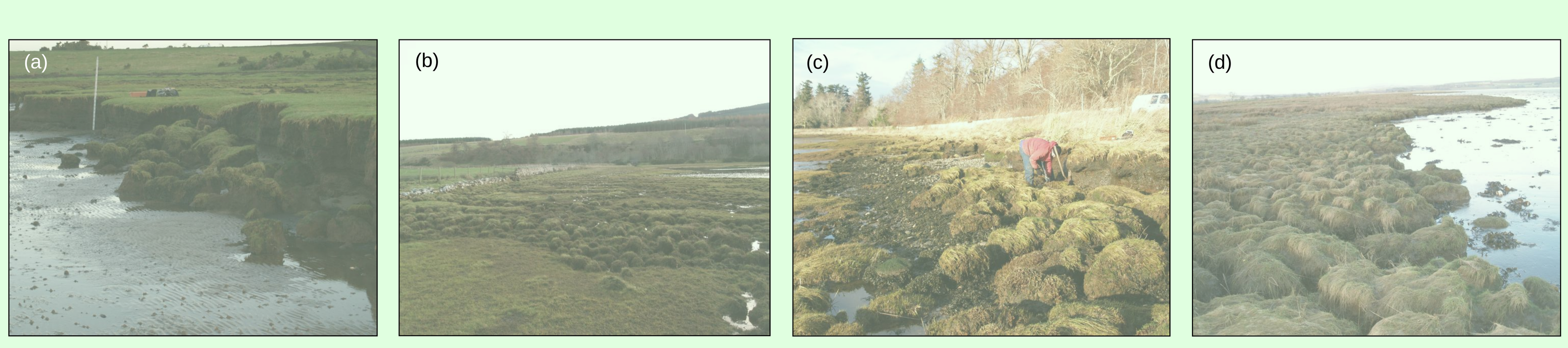


Figure 9: Erosion and deterioration of mature marshes within the Dornock Firth (a & b) and the Beauly Firth a) north shore and b) south-west site (see Figure 1)

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