University of Southampton

High Resolution Seismology, Archaeology and Submerged Landscapes - an Interdisciplinary Study

Joseph Lenham

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Abstract

Archaeological investigation of the shallow coastal environment has traditionally been conducted through exclusively marine or terrestrial methods, creating artificial division between sites located in the intertidal and subtidal zones. This thesis demonstrates a successful seamless inter-disciplinary survey methodology, utilising side scan sonar, sub-bottom profilers, aerial photography and archaeological field inspection to establish the correct spatial and contextual relationships of submerged archaeological structures. To facilitate survey of the shallow intertidal zone, a novel catamaran-based platform is developed, which carries side scan and Chirp sub-bottom sonar systems, and is proved operational in water depths greater than 1.3m and 2.4 m respectively.

Digital survey technologies offer the potential for post-survey signal enhancement of high-frequency seismic data. Investigation into the characteristics of commercial Chirp and Boomer seismic indicates that Chirp systems offer superior repeatability and vertical resolution, making possible development of a rapid, robust processing flow for high-resolution investigation of sediment structure.

Development of shoreface exploitation sites is strongly controlled by interaction between contemporary physical processes and the underlying geomorphology. High resolution seismic techniques are used here to study the drumlins, late-Quaternary seismic stratigraphy and relative sea level history of Strangford Lough, Northern Ireland. Unique seismic sections through submerged late-Midlandian (Devensian) drumlins, parallel to the direction of ice flow, indicate that adjacent drumlins share a common internal structure and are preferentially located over subtle topographic maxima in the underlying substrate. A high-resolution seismo-stratigraphy is developed from Chirp profiles through the northern lough. Correlation with field observations, cores and published RSL data from the Irish Sea suggests that Strangford Lough underwent isolation from the sea during the early Holocene, implying that early Mesolithic settlers were attracted to the area by an exploitable freshwater, rather than marine resource.

The intertidal mudflats of the Blackwater Estuary contain an extensive, but largely inaccessible and rarely exposed archaeological resource, including wooden coastal fish weirs dated to Saxon times. Application of side scan sonar to areas previously photographed during aerial reconnaissance has facilitated accurate mapping of six large (100-2000m length) structures, increasing the site record content up to 250%, and improving understanding of the manner in which these structures operated. Structures on the southern shore of the estuary extend into the subtidal zone to c. -2m OD. It is suggested that the lower altitudes of these sites imply a significantly earlier date for development of this fishing technique than presently accepted.

Dedication

To my parents and grandparents; thank you for all the years of unstinting support and encouragement.

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Contents

Chapter 1: Introduction

1.1: Rationale

Applied marine geophysical techniques have been increasingly utilised for archaeological exploration and mapping during the past 45 years of development in maritime archaeological research. The deployment of side scan sonar as a reconnaissance tool is now an important element of marine archaeological survey methodology. Early marine geophysical surveys were concerned primarily with the detection of wrecks upon the seabed, but during the early 1980's, the possibility of using sub-bottom profiling devices as a predictive tool for identifying potential sites of prehistoric settlement was recognised (Watters 1981, Van Andel & Lianos 1984,). Improvements in system resolution and positioning technologies during the following decade facilitated research into the practicalities and potential of more detailed sub-bottom surveys (Quinn, 1997). These studies investigated the possibility of imaging buried wooden structures using Chirp sub-bottom sonar (Quinn *et al*, 1997), using seismology to map and observe wreck sites (Quinn *et al*, 1998a) and the creation of dedicated seismic processing algorithms for archaeological data (Quinn *et al*, 1998b).

The perception of submerged archaeological sites as isolated entities has been superceded by the concept of the *maritime cultural landscape*, first suggested during the 1970's and subsequently defined thus, "*The maritime cultural landscape signifies human utilization (economy) of maritime space by boat: settlement, fishing, hunting, shipping and its attendant sub-cultures*" (Westerdahl, 1992). This landscape extends to the limits of maritime influence, existing wherever interaction with the sea has exerted any subsequent effect upon human activity and increasing in complexity at the physical transition between land, inland waterways and the sea. It forms a crucial link between terrestrial and maritime archaeology, most readily observed in the vicinity of *transit points*: the intersection of inland- and marine-transport routes. The local economy of transit points and their relationships with the surrounding countryside, coastal waters and their contemporaries form a major component of this landscape.

Since the last Ice Age, eustatic and regional isostatic changes in sea level have profoundly altered worldwide coastal geometries. Numerous structures relating to shoreface exploitation and maritime transit have therefore undergone marine inundation and exposure, preserving or destroying evidence for past activity within the coastal zone. During the 1990's, recognition of the importance of the inter-tidal archaeological resource led to a nationwide desk-based study conducted by English Heritage and the Royal Commission on the Historical Monuments of England (Fulford *et al*, 1997), which acknowledged the importance, fragility and irreplaceable nature of coastal archaeological sites. Although this study concentrated on the inter-tidal resource, it also made the crucial point that historic landscapes extend seamlessly between dry land and the sub-tidal zone, c.f. Westerdahl (1992). It is now widely acknowledged that accurate information upon the local sea level history, active site processes and sedimentary evolution of marine sites is necessary for correct contextual establishment of any artifacts and structures discovered (Watters 1981, Fulford *et al* 1997). Accordingly, the International Council on Monuments and Sites (ICOMOS) has adopted the Venice Treaty (ICOMOS, 1996), which proposes that maritime heritage sites be examined *in situ* by non-penetrative means.

The most effective method of surveying a seamless landscape should be similarly continuous across the inter-tidal zone, however, physical differences between the marine and terrestrial environments preclude the use of a single survey device. Additionally, the diverse hydrodynamic regime of the inter-tidal and shallow sub-tidal zones presents additional problems, necessitating a modified, interdisciplinary approach to archaeological survey. Traditional approaches are precluded by tidal currents, underwater visibility, sediment liquefaction, short and infrequent periods of tidal exposure, and navigational obstacles. A safe, rapid and effective survey methodology built upon compromise between traditional terrestrial and marine investigative techniques must therefore be established if the inter-tidal zone is to be thoroughly explored. This thesis will examine the use of high-resolution marine seismic survey systems as part of a broader inter-disciplinary methodology, to investigate these archaeologically-rich environments.

1.2 Thesis Aims

This thesis will:

(1) Develop a methodology for the application of high-resolution seismic survey techniques within the inter-tidal zone, as part an integrated marine archaeological survey methodology.
(2) Investigate the potential for rapid, effective processing of digital high-resolution seismic data and compare the suitability of Chirp and Boomer sources for shallow-water survey applications.
(3) Investigate selected sedimentological and archaeological problems by application of high-resolution seismology.

These investigations are supported by geophysical survey data from two areas of the United Kingdom: Strangford Lough in Northern Ireland and the Blackwater Estuary, Essex (fig. 1.1).

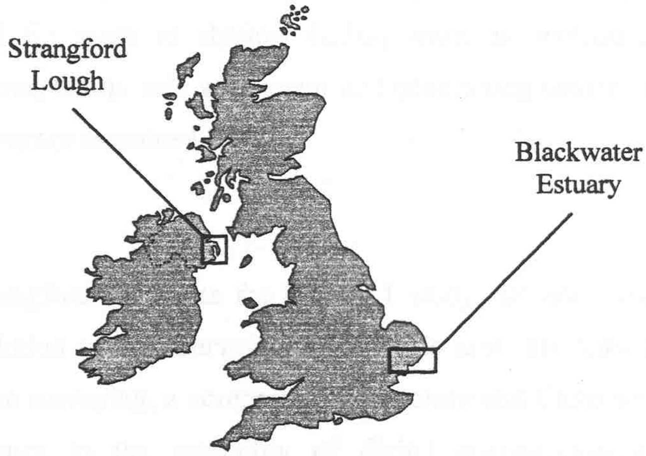

Fig. 1.1: This thesis presents geophysical survey data from two areas: Strangford Lough (Northern Ireland) and the Blackwater Estuary (Essex).

1.3: Synopsis

Inter-disciplinary integration within inter-tidal maritime archaeology is essential. Despite this, this thesis has been subdivided into two general themes: seismic determination of palaeolandscapes and side scan sonography of the inter-tidal zone for archaeological purposes. This division arises from the type of equipment used and the data generated. In Theme 1, sub-bottom profilers operating in an effectively vertical plane are employed to determine palaeo-surfaces reflecting sequential change in the local environment. Theme 2 is concerned with the use of side scan sonar, which maps structures protruding from the seabed, at frequencies two orders of magnitude greater. Processing and interpretation of these two data-types is entirely separate. The problems addressed are also quite different, so division into Themes lessens interruptions in the progressive discussion of each area. Conclusions arising from these separate themes are subsequently integrated during the Discussion, Chapter 8. A brief synopsis of Theme 1 and 2 chapter content is as follows:

Chapter 2 is concerned with the practicalities of shallow water seismic acquisition. A novel catamaran designed for work in shallow (1.3m) water is presented and the characteristics of the Boomer, Chirp, side scan sonar and positioning devices employed within the following chapters are examined.

Theme 1

Chapter 3 introduces Strangford Lough as the Theme 1 study site and discusses the effectiveness of high-resolution seismic surveying within this area. To demonstrate the effectiveness of dual-source surveying, a comparison of Boomer and Chirp seismic data is presented, with reference to the suitability of digital post-processing. Further information on digital processing of Chirp data is presented in **Appendix I.**

Chapter 4 is an investigation into the internal structure of drumlins, which are subglacial elongate bedforms whose genesis is not properly understood. It is argued that the use of marine seismology in this instance provides a rapid, objective, non-destructive method of examining the internal structure of these bedforms and offers the opportunity to examine the relationship between drumlins and the underlying substrate. It is archaeologically important to understand the underlying glacial landscape, as it controls the development of subsequent physical surfaces, which in turn influence the spatial and temporal distribution of anthropogenic activity.

Chapter 5 presents high-resolution seismic stratigraphic data from Strangford Lough, demonstrating that Chirp sources possess the capability to produce highly detailed images of the subsurface. This information has a range of applications, including assisting in sea level studies and identifying archaeologically significant horizons. It is demonstrated that previous shorelines and sedimentation in Strangford Lough were largely dictated by the underlying drumlin topography. Sea level information suggests that during the early Mesolithic settlement of Ireland, Strangford Lough was a large freshwater lake, implying major differences in the attraction and usage of this area at this time.

Theme 2

Chapter 6 reviews the need for a rapid, remote means of inter-tidal archaeological surveying, which is the focus of Theme 2. Coastal fish weirs are identified as suitable targets for an investigation into the potential suitability of high-resolution marine seismology - particularly side scan sonar - as a major element in an integrated survey methodology. Coastal fish weirs form an important part of the archaeological resource, as they provide important information upon local industry. These sites are identified as being at risk due to rising sea levels and encroaching development; development of a suitable survey methodology is thus extremely important.

Chapter 7 demonstrates the effectiveness of side scan sonar as a tool for inter-tidal site mapping. The results of the initial system calibration over stone fish weirs in Strangford Lough are presented, demonstrating the ability to detect inter-tidal archaeological structures. Description of a subsequent, major inter-disciplinary survey of wooden weirs in the Blackwater Estuary, Essex follows.

Chapter 2: Survey Systems

Overview

This chapter contains discussion on the practicalities of shallow-water seismic acquisition for the study of submerged landscapes. The choice and specifications of navigation and acoustic survey tools are described; of particularly importance is the resolution of the tools selected as this determines the limits of what might be achieved. A novel, shallow water catamaran platform for Chirp and side scan surveying is introduced, which extends the practical range of side scan deployment to water depths of 1.3m, and that of Chirp to 2.4m, facilitating survey within the shallow inter-tidal zone.

2.1 Introduction

The use of High-resolution sub-bottom profilers and side scan sonar as investigative tools within the shallow marine and lacustrine environments has become increasingly common during the past four decades (Fish & Carr 1990). Major applications of these tools include slope stability studies, aggregate volume determination, wreck location and geotechnical property determination within civil engineering surveys. Until the 1990's, it was often difficult or even impossible to conduct rapid, precise surveys within the shallow sub-tidal and inter-tidal zone. This difficulty was caused by a lack of accurate, easily deployable real-time positioning systems and the limited resolution of the available shallow seismic survey equipment. During the 1990's, three major advances in marine surveying technology resulted in the availability of accurate marine survey and positioning systems to academic research groups. These advances were: an increased availability of higher computing power, improved survey system capabilities, and the launch in 1985 of the United States' Global Positioning Satellite navigation system. Combination of these factors has facilitated the high-resolution, accurately positioned surveys described within this thesis. All equipment utilised during the course of the projects - other than the catamaran frame, which was custom built - is commercially available.

2.2 Positioning Technology

Global Positioning Satellites (GPS) provides non-US-military receivers with earth-surface positional data generally accurate to the order of tens of metres. Improved positioning accuracy is available via a network of commercial transmitters, which broadcast a calculated *differential* (DGPS) signal, compensating for the deliberate "dithering" of the signal imparted by the military programmers. The service provider utilised during the 1998 Blackwater Estuary survey (Focus FM) supplied positional corrections accurate to ±1m accuracy. In 1997, network coverage did not extend to Strangford Lough, so an alternative, line-of-sight VHF radio system was implemented. In such a system, a VHF transmitter and GPS receiver are installed at a precisely determined location close (within 20km) to the survey site, and the difference between the received GPS and true base station positions is relayed to the ship. Such a system can provide horizontal positioning corrections accurate to ±1 metre at a rate of approximately $1s^{-1}$. Positioning accuracy was a key element within the fieldwork described in the following chapters, as it facilitated accurate pre-planning of survey lines from existing aerial photography and field data. It also enabled precise relocation of sites of interest and the execution of successive survey lines utilising multiple marine seismic systems.

2.3 Selection of Seismic Source

The selection of a specific acoustic source for any marine seismic survey is governed by two factors: the required resolution and the depth at which the target lies buried. The vertical and horizontal resolution of seismic data are loosely defined as the minimum spatial separation of two reflecting bodies such that they can still be imaged as individual discrete units (See Appendix 1). Seismic source resolution is largely controlled by frequency content; higher frequencies (broader bandwidths) result in higher vertical and horizontal resolutions. The propagation of acoustic energy through the water column and sub-surface results in energy loss due to spherical spreading of the wave front, attenuation by inter-granular friction loss and the reflection coefficient of each material interface crossed (Sheriff & Geldart, 1995). Higher frequencies suffer a higher energy loss per unit path travelled than low ones, thus low frequencies achieve a greater vertical penetration per input energy. As a consequence of this, all seismic sources are forced to compromise between penetration and resolution. Modern marine seismic sources range in frequency from 10 Hz (tens of km penetration, 30m plus resolution) used for the imaging of deep Earth structures (Klemperer & Hobbs, 1991), to 150 kHz (< 4m penetration, 2cm vertical resolution) (Lambert *et al*, 1999), designed for mine detection purposes. An evaluation of modern high-resolution survey technologies is presented by Mosher & Simpkin (*in press, 1999*).

Reconstruction of palaeo-landscapes requires decimetric resolutions in certain circumstances and penetrations of tens or even hundreds of metres in others. No single commercially available source was considered capable of operating to these standards; as an alternative, two separate sub-bottom profiling devices linked to a common digital recording system, were employed. Real time DGPS facilitates acquisition of precisely overlapping survey lines, allowing the determination of the inter-relationship between shallow (3-25m) and deeper (20-100m) geological surfaces through multiple passes with differing sources. The sub-bottom profilers used during work described in this thesis are of the Boomer and Chirp type (see below), both built by GeoAcoustics™ (Great Yarmouth, UK). The digital acquisition system employed was a GeoAcoustics™ Sonar Enhancement System, which records directly to disk and Exabyte tape in an industry-standard Seg-Y format. Both Boomer and Chirp data can be written to this format and subsequently extracted for post-processing in a dedicated seismic package, e.g. Landmark Geophysical's ProMAX™.

Combination of two sub-bottom profilers reduces the compromise between resolution and penetrative depth. The Boomer source is capable of penetrating glacial till with a depth-dependent vertical resolution[1] of 60-100cm, whilst Chirp provides higher vertical resolution data (35cm, see Appendix I). By way of example, Boomer data presented in Chapter 4 exhibits clear reflections from bedrock located 50-70 metres below the surface of glacial till, whilst the Chirp pulse rarely propagates further than 25 metres in soft sediment and cannot penetrate hard sands or till. Fundamental differences in the principle of operation, rather than the frequency content of the two sources are responsible for this contrast in acoustic capability (Chapter 3).

2.4 Boomers

Boomer systems operate by the electrostatic impulsion of an approximately horizontal aluminium plate (Darling, 1999) which rapidly displaces the underlying water and generates a down-going pressure wave. A typical system configuration is shown in figure 2.1 (below). The returning pulse is collected in a single channel 20-element hydrophone streamer and is digitally recorded. In order to preserve near-vertical incidence in the reflected signal, it is necessary to tow this streamer adjacent to the source (fig. 2.2). This method also minimises the direct-wave arrival time and utilises the engine wash to break up this arrival. The geometry described allows a practical minimum survey draught of c. 7 metres when using a 105 J GeoAcoustics source, although other systems (e.g. Simpkin & Davis, 1993) achieve working depths of < 2m at the expense of easy manual deployment.

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[1] All resolutions pertaining to systems deployed in the course of this thesis refer to the actual resolution observed in the final processed data. It is common practice amongst seismologists to refer to the near-field source resolution, which is a measure only of the potential source resolution and neglects the effects of attenuation, divergence and ambient noise pollution. Dependent on the criteria employed, the Boomer and Chirp systems described here might possess theoretical vertical resolutions of c. 20 cm and 12.5 cm respectively (Appendix I & Quinn, 1997), based upon marketed, laboratory-measured source frequency values. These values result from using ($\lambda_d/4$) as evaluative criterion, where λ_d is the wavelength of the dominant source spectrum frequency at the depth of interest. Resolutions quoted in the main text are practical values directly relating to the data described in the following chapters; the frequency content of field-recorded data is uniformly lower than laboratory values.

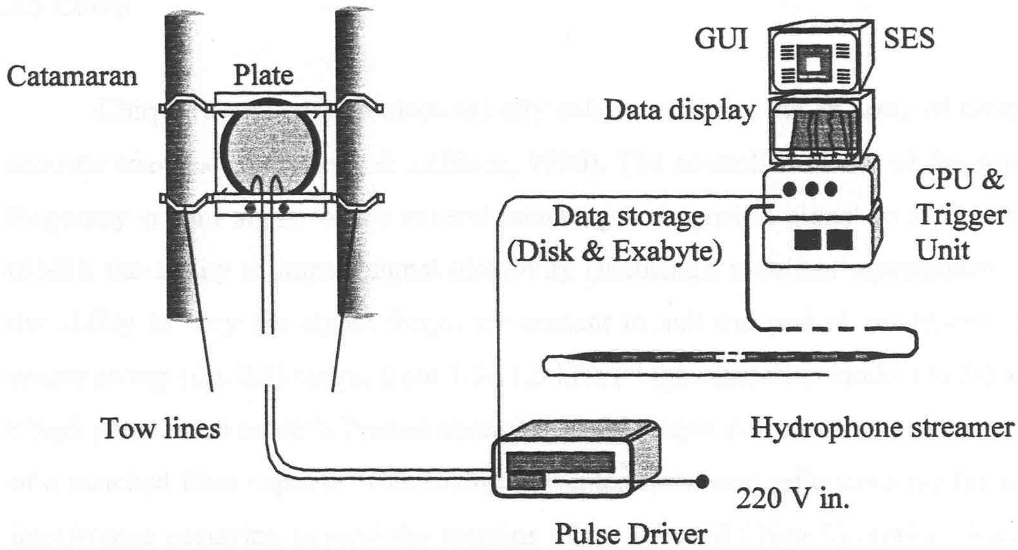


Fig. 2.1: Typical acquisition configuration for the GeoAcoustics™ Boomer system. Triggering is set in the CPU, which controls the timing of the pulse and recording units. Data is recorded to tape or disk in a form of the industry standard Seg-Y format. Navigation and tidal data are recorded separately and spliced into the Seg-Y header either prior to processing or during any subsequent digitisation.

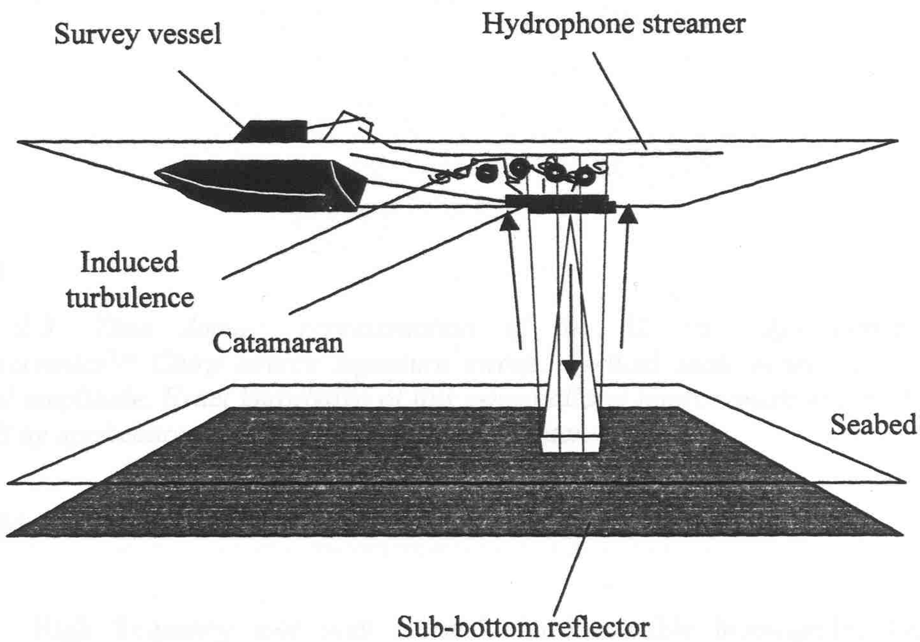


Fig. 2.2: Operation of surface-towed boomer system. Turbulence is induced between the source and receiver to reduce the direct wave arrival. A great improvement upon this method is offered by housing the source and receiver within acoustic baffles (Simpkin & Davis, 1993), but towfish size precludes deployment from most small vessels of convenience.

2.5 Chirp

Chirp systems emit an electronically calibrated signal via an array of ceramic acoustic transducers (Schock & LeBlanc, 1990). The controlled nature of the swept-frequency output signal offers several advantages: improved signal to noise ratios (SNR), the ability to impart signal directivity (focusing), excellent repeatability and the ability to vary the signal frequency content to suit the seabed conditions. The source sweep (fig. 2.3) ranges from 1.5-11.5 kHz ("high-resolution mode") to 2-8 kHz ("high penetration mode"). Precise control over the output pulse facilitates application of a matched filter capable of removing unwanted noise and reflections modified by interference occurring beyond the margins of the focused Chirp "footprint". Further details of Chirp sonar signal processing are described by Quinn (1997) and Quinn *et al* (1998b).

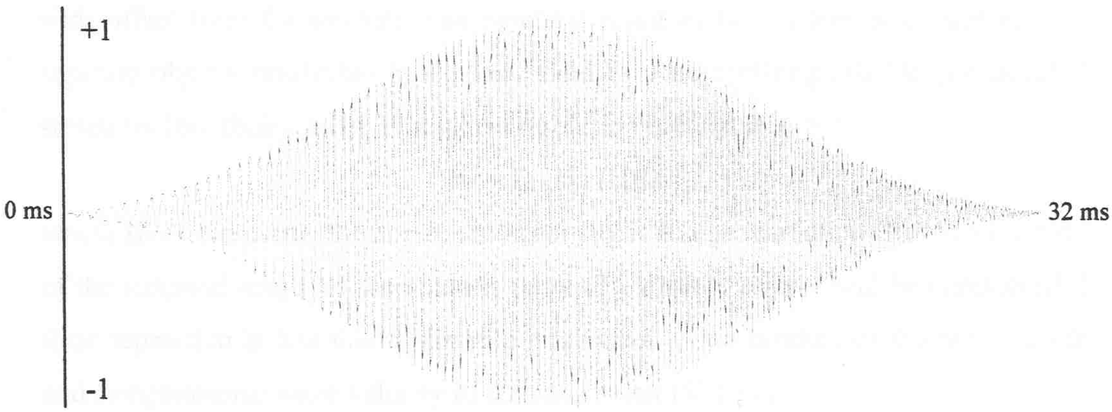


Fig. 2.3: Time domain representation of the 32 ms "high penetration" GeoAcoustics™ Chirp source signature sweep. Vertical scale represents relative signal amplitude. Exact knowledge of this sweep allows improvement of data SNR to 80 dB by application of a matched (correlative) filter.

2.6 Side Scan Sonar

High frequency side scan sonar is an invaluable investigative tool for determination of the spatial distribution of sediment and structures on the seabed. The first short-range side scan device was developed in 1963, for shipwreck location (Fish & Carr, 1990). Since then, 500 kHz side scan units have been demonstrated as capable of providing highly detailed images of wrecks and other seafloor targets (e.g. Quinn *et al*. 1999, Fish & Carr 1988).

Side scan transceivers are constructed from piezo-ceramic plates geometrically arranged such that electrical excitation produces a narrow vertically-orientated beam of high frequency acoustic energy (Fish & Carr, 1990). These transceivers are conventionally mounted back-to-back within a towfish, which allows continuous profiling to both port and starboard as the fish progresses forwards (fig. 2.4). Backscatter from seabed irregularities at a granular level and above is returned to the transceivers between pulses and recorded digitally. The relative amplitude of the received backscatter is proportional to grain size and larger-scale seabed morphology.

The effective resolution of side scan sonar is divided into two elements, termed *transverse* (track-parallel) and *range* (perpendicular to the ship track) resolution by Fish & Carr (1990). Transverse resolution (R_T) is dependent upon the sonar pulse beam width, vessel speed and ping rate. As beam width increases (spreads) with distance from the source (D), the transverse resolution will decrease with offset from the towfish. The practical result of this is that at greater ranges, separate objects resolvable in the near field may be indistinguishable and detailed structures lose their clarity. Transverse resolution is calculated thus:

$$R_T = D \,.\, \sin(\mathrm{HBA})$$

where HBA represents the horizontal beam angle. Range resolution (R_R) is a function of the temporal length of the acoustic pulse (T); distinct objects will be unresolved if their separation is less than a distance equivalent to the product of the pulse length and compressional wave velocity of sound in water (V_p), i.e.

$$R_R = T \times V_p$$

The system utilised in all surveys described in this volume is a GeoAcoustics™ dual frequency side scan sonar, which operates at 60 and 410 kHz (commonly referred to as "100" and "500" kHz modes), producing a maximum seabed coverage of 72m per channel. Calculation of resolution for "500 kHz" mode yields a range resolution of 0.13m and transverse resolution of 0.62m (at maximum range). The lower frequency ("100 kHz") mode is necessary in areas of deeper water, where divergence and attenuation prevent adequate high frequency signal return. Range resolution at this frequency is 0.25m and transverse resolution 1.26 (max range). It is common practice to acquire shallow-water side scan data on parallel survey lines spaced 100m apart. If this grid can be rigorously followed, the range resolutions for 500 and 100 kHz side scan data at the point of overlap will be 0.43m and 0.88m respectively.

2.7 A Novel Platform Allowing Extremely Shallow Water Side Scan Deployment

The extreme shallow water environment of the inter-tidal zone necessitates a new approach to side scan survey technique. Danger of fouling on submerged topographic or structural projections represents a significant risk, and towfish positioning becomes extremely important if accurate spatial delineation of submerged sites is the object. Furthermore, the beam angle of the acoustic transceivers dictates that the fish be flown as close to the sea surface as possible, in order to maximise the available slant range. Previous attempts to solve these issues elsewhere had included practices such as mounting towfish on the hull of small craft and operating the side scan on a single channel. A more elegant solution to these issues was devised specifically for this investigation, using the development catamaran originally supplied by GeoAcoustics for shallow - water chirp survey off small vessels. The side scan transceivers are removed from their towfish and mounted upon a hinged arm (fig. 2.4) which locks them into place beneath the flotation pontoon of the catamaran. This position maximises the available water depth and allows simultaneous operation of Chirp and side scan sonar. The entire system weighs approximately 100 kg, providing inertia against high frequency swell and important stability for the transducers. Strategic attachment of towing lines allows a degree of steering from the stern in the event of near-collision with buoys or floating debris.

Figure 2.4 shows the first-generation model of the catamaran, used during survey work to be described within this volume. The high quality of data resulting from catamaran use (e.g. fig. 2.5) justifies additional refinement, particularly in the positioning and streamlining of the system. At present, position is calculated by means of programming a fixed antenna-catamaran offset into the DGPS logger. This could be improved by the use of a second GPS receiver mounted upon the catamaran, although this creates problems with respect to masking noise generated by signal reflection from the sea surface. Streamlining of the catamaran is more important, as the current design creates turbulence, which sometimes masks the vertically-incident port channel return.

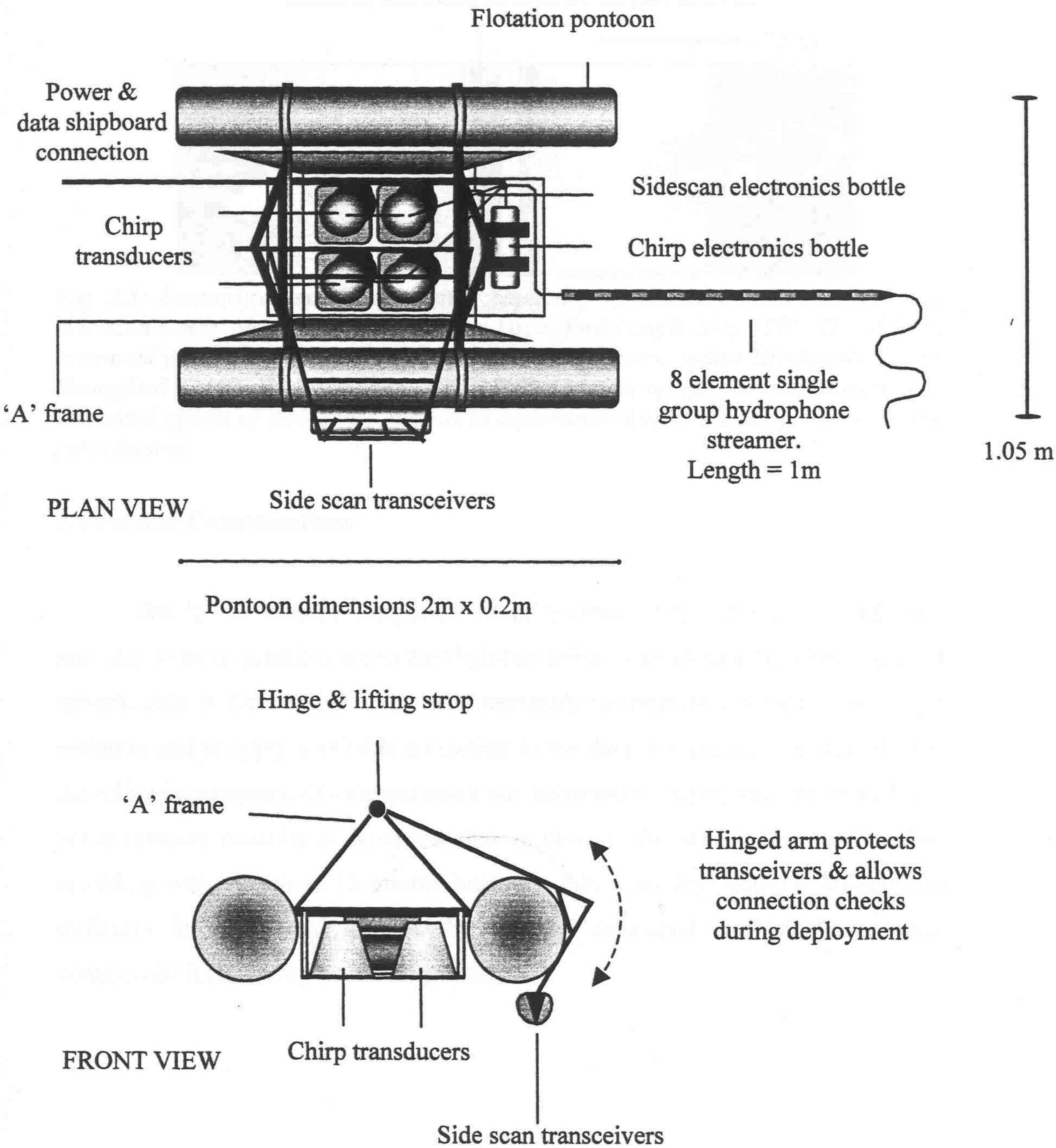


Fig. 2.4: Combined surface-towed Chirp & side scan catamaran designed and built at Southampton Oceanography Centre and carrying GeoAcoustics™ transducers. Stability is provided by the inertia of the Chirp transducers, whilst the catamaran structure protects the transducers against collisions. Hinging the side scan transceiver mounting facilitates checking of connections without shipboard retrieval and allows the transceivers to lift in case the system enters water shallower than 0.35m.

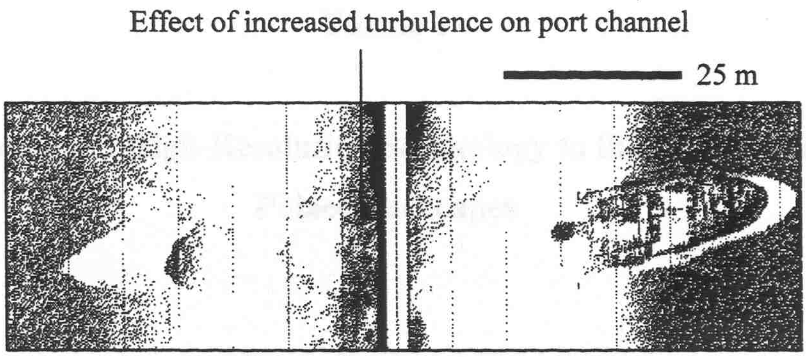


Fig. 2.5: Demonstration of the imaging capability of catamaran-mounted 500 kHz side scan sonar, acquired during tests on Strangford Lough, May 1997. The 185 ton armoured yacht Alasdair was sunk in 18-25 metres of water within Ringhaddy Sound, Strangford Lough, 1946 (Wilson, 1997) and now sits upright on the seabed. The unwanted effects of turbulence related to catamaran drag are clearly visible on the port channel.

2.8 Further Considerations

The "z" or altitude component of differential GPS is not yet of sufficient accuracy to be of practical use to the High-resolution seismologist. In order to correct seismic data to Ordnance Datum, it is necessary to measure the local tidal height variation and to apply a suitable correction to the data. For the surveys described in the following chapters, this measurement was achieved by deployment of an analogue water pressure recorder at protected sites as close to the survey areas as possible, recording water depth at 15 minute intervals. Future surveys could overcome this difficulty by employing one of the recently developed and highly accurate, commercial RTK survey positioning systems.

Theme 1

Applications of High-Resolution Seismology to the Investigation of Palaeolandscapes

Chapter 3: Introduction to the Survey Area and Seismic Investigation

Overview

Theme 1 investigates the applications of high-resolution seismology to glacial sedimentology and soft sediment seismic stratigraphy. In this chapter, survey work executed in Strangford Lough, Northern Ireland, is described. A comparison of Boomer and Chirp sub-bottom profiler data is presented, before and after post-processing. This comparison differs from those published elsewhere, which have concentrated on laboratory-type studies of source signature, directivity, etc. The results of this comparison indicate that combined deployment of Boomer and Chirp sub-bottom profiling systems should produce a significantly broader range of information on the sub-bottom structure of the survey area. It is argued that the results of this investigation are of general interest to potential inter-disciplinary users of high-resolution profiling systems.

3.1 Introduction

Most sub-bottom profiler surveys are undertaken with the specific objective of tracking major seismically reflective horizons, such as the upper surface of bedrock, shallow gas or the limits of submarine aggregate bodies. The resolution afforded by modern profilers is sufficient to investigate the overlying and intermediate strata at a greater level of detail than is commonly required. If the geomorphological evolution of a region is to be studied for archaeological purposes, then the study must extract information at the maximum possible resolution and also consider the effects of underlying units upon the shaping of more recent landforms.

The area selected for this study of landscape evolution is Strangford Lough, a sea lough on the eastern coast of Northern Ireland (fig. 3.1). The lough is approximately 20km in length, 7km at its greatest width, and linked to the Irish Sea by a narrow channel approximately 8km in length, known locally as "The Narrows". This channel narrows to just 500 metres width and 23 metres depth at its northern end; a tidal range of c. 3.6m within the lough produces currents up to 4 ms^{-1} at this point during peak tidal flow.

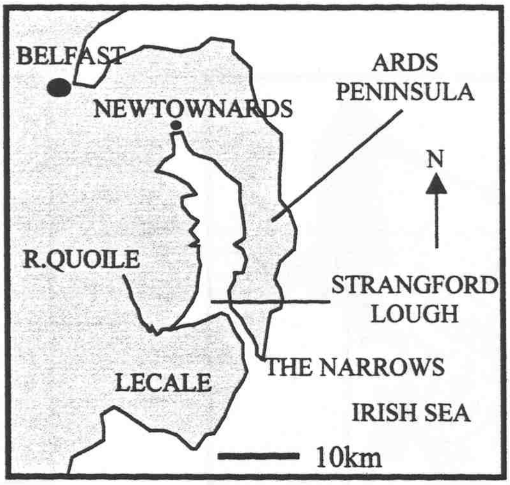


Fig. 3.1 Location of the study area described in Theme 1. Strangford Lough is a sea lough approximately 22km in length and 7km across at its widest point. It is linked to the Irish Sea by a narrow, 8km long channel known locally as "The Narrows", which is at one point merely 23 metres deep.

During the late Quaternary, this area underwent at least two major episodes of glaciation, the most recent of which produced widespread swarms of drumlins, approximately 14700 BP (McCabe & Clark, 1998). Eustatic and glacially-related isostatic shifts in relative sea level, have resulted in a regionally variable post-glacial sea level curve along the coast of north-east Ireland (fig. 3.2).

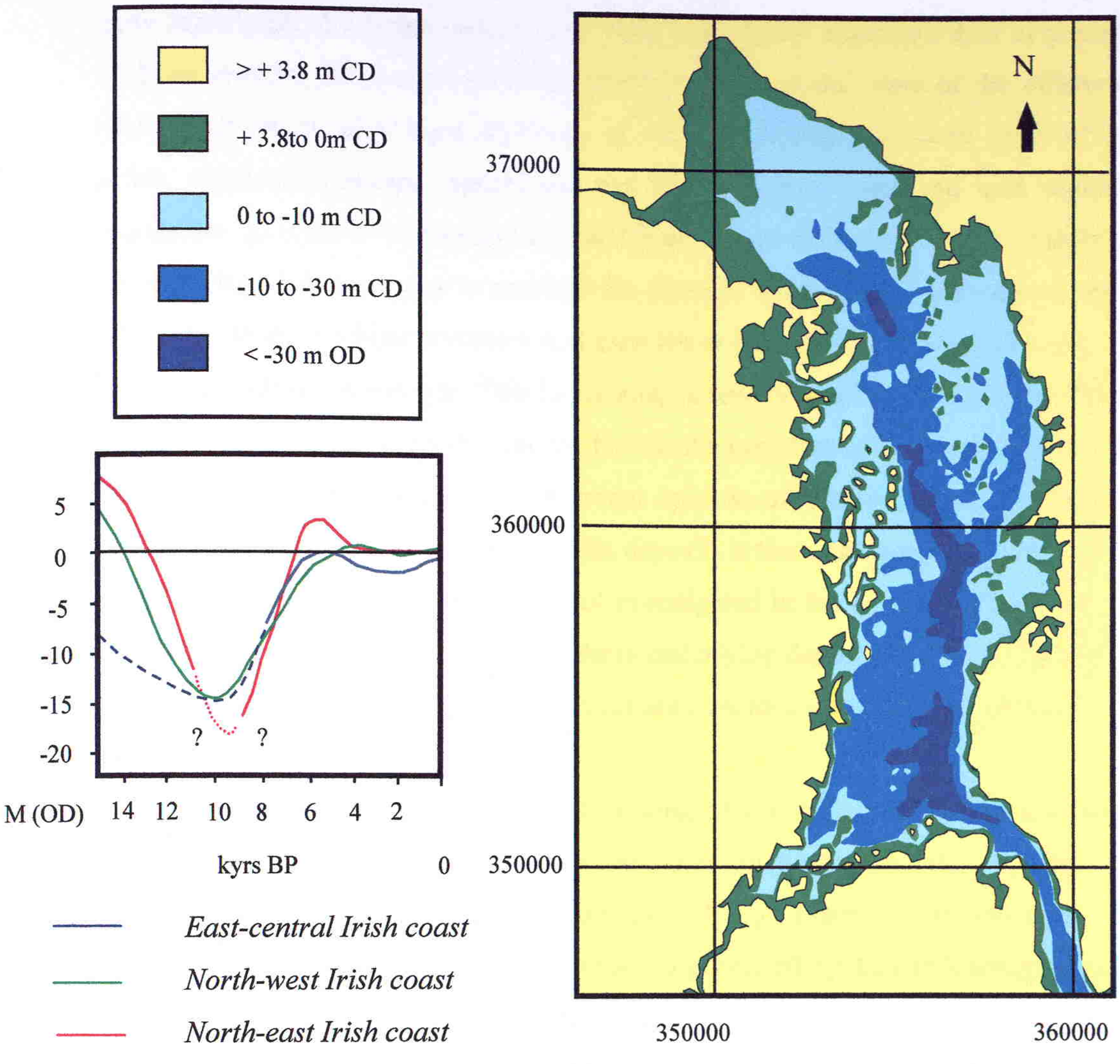


Fig 3.2: Sea level curves for the northern Irish coast & sketch bathymetry of Strangford Lough. Dashed lines represent conjectural trajectories (After Carter et al, 1989). Reduction of sea level within the lough to the -15m contour or lower would suggest that in the early Mesolithic, exploitation of the shoreface would have occurred upon surfaces which have since been inundated. This view may be overtly simplistic, as it does not take into account the effects of sedimentary and hydrodynamic processes acting upon this surface. Bathymetric source: Admiralty Chart 2159.

The earliest known settlement of this region occurred c. 9000 BP. Early Mesolithic flint-working sites have been discovered around the north-east coast and a large number of Mesolithic sites are known from the Strangford Lough region (McAuley, 1996). It is probable that changing sea levels during the Holocene exerted a direct control upon the manner in which the area was settled. It is immediately obvious from the existing sea level curve that marine transgression has drowned much of the early Mesolithic foreshore beneath 20-30 metres of water and thus, during the early Mesolithic, the lough would have been less areally extensive than at present. Such an exercise in contour-reduction produces a simplistic view of the effects of post-glacial sea level change, however, as no consideration has been made of the active physical processes controlling and resulting from localised and regional inundation. In order to understand the landscape which these early settlers inhabited and exploited, it is necessary to consider the changes which have occurred as a result of the dominant physical processes and how these processes were controlled by the pre-existing glacial landscape. This landscape, in turn, was affected by the results of preceding geological and glacial events, but for the purposes of this investigation, the earliest event of interest is the most recent episode of drumlinisation. The glacial surface underlying the most recent drumlin deposits is thus considered by this study to represent geological basement, and is not investigated in the course of the following chapters. Only a general description of these underlying deposits will be given during this chapter, although extensive publications are available elsewhere (e.g. Smith *et al*, 1991).

Assessing the possibility of using existing survey technology to investigate the inter-relationship between process, landform and landscape exploitation within an evolving marine landscape forms both the methodological core of this thesis and the main purpose of this chapter. The information produced by this technology can be easily misunderstood or over-interpreted, if the adopted survey and processing methodologies are insufficiently understood. This chapter is concerned with the description and evaluation of a suitable methodology, presenting data from Strangford Lough as evidence. Suitable processing algorithms for best use of Boomer and Chirp data are presented, although to improve cohesion, a more detailed discussion of optimal Chirp processing parameters is presented in Appendix I.

3.2 The Underlying Geological Deposits of Strangford Lough

Bedrock occurs at or near the surface in approximately one third of the area surrounding Strangford Lough and Newtownards (Smith *et al*, 1991). The Ards Peninsula and western shore of Strangford Lough are comprised mainly of Ordovician - Silurian Strangford Group shales and grits which were deformed by the Caledonian Orogeny to produce tight folds with a NE - SW strike and associated NE-SW / NW-SE faulting (BGS sheet 37 /38).

Strangford Lough lies above a half graben bounded to the east by the Newtownards Fault. Subsidence on this fault began during the Carboniferous, as evidenced by rare outcrops of the Castle Elspie Limestone, although the most significant infilling of the subsiding half graben occurred during Permo-Triassic time. This sedimentary fill comprises three main subdivisions: the basal Enler Group (L. Permian), the Belfast Group (U. Permian) and the overlying Sherwood Sandstone Group (Triassic), the distribution of which between Strangford and Belfast Loughs suggests that it oversteps the former P-T deposits. The Sherwood Sandstone consists of fine to medium grained sandstones with subordinate mudstone and siltstone intercalations (Smith *et al*, 1991). Deposits lying proximal to the Newtownards Faults have undergone syntectonic fault-parallel folding to high angles, but the general disposition of the sandstone is a shallow (<20°) easterly dip towards the fault.

Geological maps suggest that the bedrock - till interface beneath the lough is likely to truncate either Triassic Sherwood Sandstone or Silurian Strangford Group shales and grits, which should be differentiable by their contrasting structural styles in seismic section.

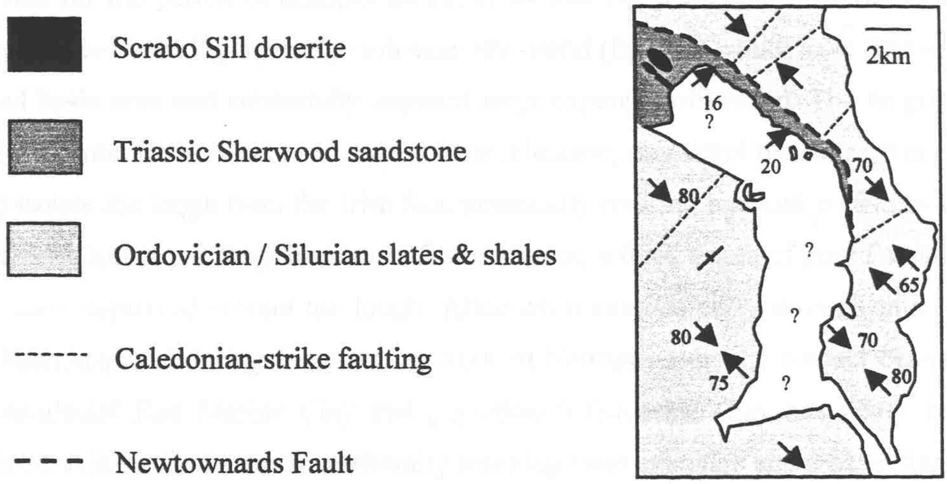


Fig. 3.3: Geological sketch of the Strangford Lough area, after BGS sheets 37 & 38.The lough is underlain by steeply dipping Silurian / Ordovician slates and shales and sits in a half-graben formed on the Newtownards Fault. Sedimentary infilling of this half-graben began in the Carboniferous, although field descriptions of the Castle Elspie limestone are rare. Northern areas of the lough are underlain by Permo-Triassic sediments; predominant and uppermost in the succession is the gently dipping Triassic Sherwood sandstone which outcrops around the eastern shore, close to the Newtownards Fault. Boreholes drilled to delimit the Sherwood aquifer provide important information upon the post-glacial development of Strangford Lough.

Glaciation of the surrounding land has produced drumlinisation of the Midlandian (Devensian) till deposits; Strangford Lough lies 8km from the north-eastern end of a 150km long drumlin belt (McCabe & Dardis 1989, fig 1). There are examples of rock-cored drumlins exposed in the area surrounding Strangford Lough, whilst many others within this section of the drumlin belt are cored by an older lower till unit. The spatial distribution and individual geometries of the Co. Down drumlins were studied by Vernon (1966, 1971), who measured axial ratios and spatial separation of the terrestrial drumlins around Strangford Lough and azimuthal values for those partially drowned and eroded drumlins (*pladdies*) which lie within the intertidal zone. The presence of completely drowned drumlins beneath the lough is suggested both by the existence of these pladdies and by Admiralty chart data (1976). Imaging the internal structure of these drumlins constitutes the topic of Chapter 4; in the following sections the acquisition, processing and general methodology employed will be described.

Late-, post-glacial and recent sedimentation within the lough has received less attention than the surrounding drumlins. Late-glacial deepwater marine conditions are suggested for the period of drumlinisation: c. 14 700 BP (McCabe & Clark, 1998). Falling sea levels during the early Holocene low-stand (fig. 3.2) would have gradually reduced basin area and subaerially exposed large expanses of seabed. The height of this RSL minimum in Strangford Lough is problematic, as a level beneath -23m OD would isolate the lough from the Irish Sea, potentially creating brackish or freshwater conditions. During recovery from the RSL minimum, a thick series of grey Estuarine Clays were deposited around the lough. Although numerous cores through this unit have been acquired during construction work in Newtownards, the contact between the late-glacial Red Marine Clay and post-glacial Estuarine Clay has never been described. It is likely that an unconformity resulting from exposure and erosion during the early Holocene RSL minimum will be visible through seismic profiling. Investigation of the late- and post-glacial sedimentation and relative sea level history of Strangford Lough is described in Chapter 5. In this chapter the quality of the high-resolution data upon which this investigation is based is discussed.

3.3 Survey Details

Seismic surveying within Strangford Lough was conducted between May 29th and June 5th 1997, utilising a 105 J. GeoAcoustics GeoPulse Boomer, GeoChirp Chirp profiler and dual frequency (100/500 kHz) side scan sonar (see Chapter 2). Approximately 100km of Chirp & 100 kHz side scan, 29km of Boomer and 25km of 500 kHz side scan data[1] was acquired (fig. 3.4). Positioning was achieved to an accuracy of ± 1m, utilising a line-of-sight DGPS correction unit mounted on the nearby Scrabo Tower (GR 477727). Tidal monitoring was conducted using a portable water level recorder mounted on southern Mahee Island (GR 538641).

[1] Described fully in Theme 2, which discusses artefact location and structural mapping within the inter- and shallow sub-tidal zone.

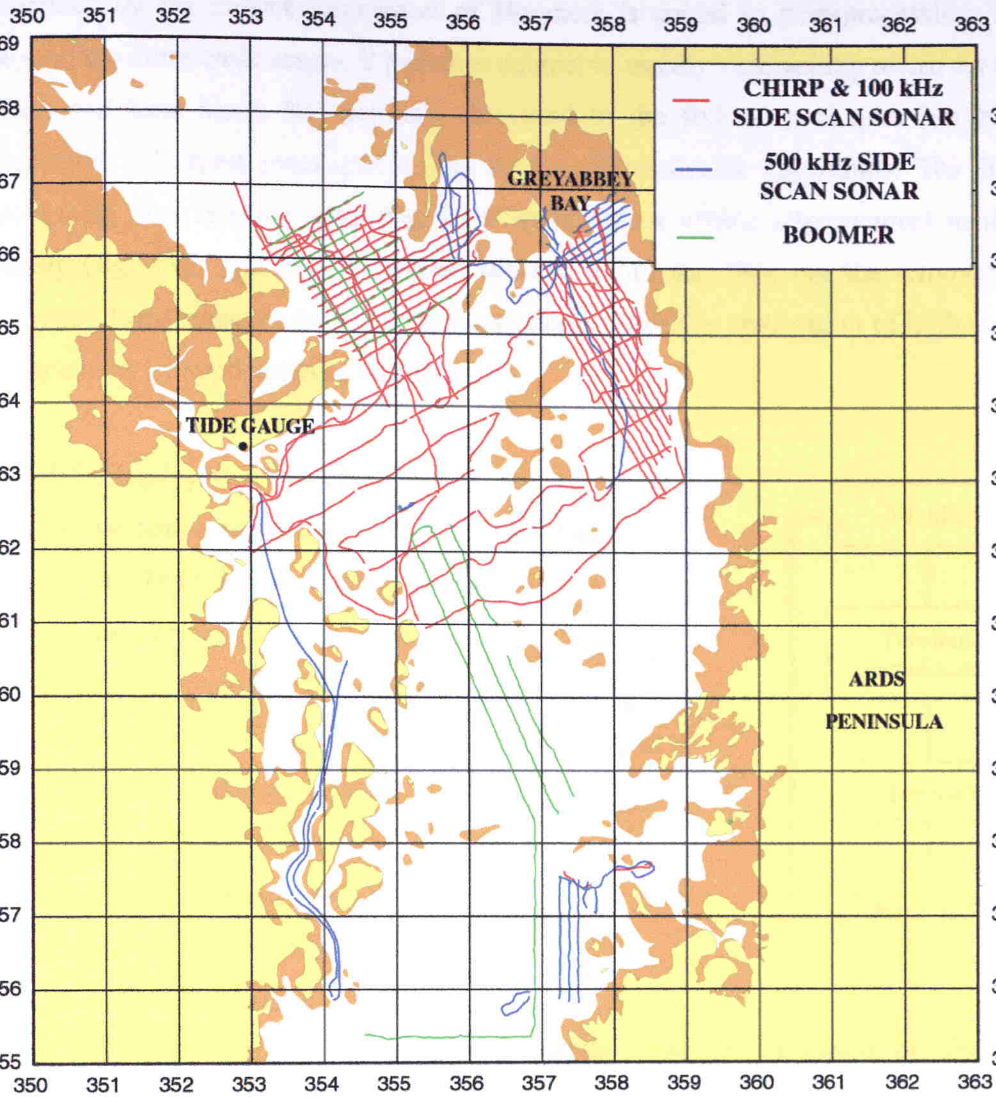


Fig. 3.4: Coverage plot for high-resolution seismic survey data acquired in central and northern Strangford Lough during May / June 1997. Grid spacing is 1km.

In the northern basin the survey was enhanced by the addition of 85km of superimposed and intermediate parallel GeoAcoustics GeoChirp sub bottom profiles and 100 kHz. side scan coverage, at 150 metre line spacing. Both sub-bottom profilers were mounted upon towed catamarans, which facilitated their operation in shallow water (see previous chapter).

3.4 Seismic processing

The advantages of routine post-processing for digital high-resolution seismic data have previously been discussed (Haynes *et al* 1993, *Quinn et al* 1998b). Data produced by the current generation of Boomers is suited to post-processing, but beyond the more basic stages, it becomes subject to rapidly diminishing return for the effort and time input. Boomer data discussed in the following chapter has been processed, following investigation and testing of applicable algorithms. The final processing flow is quite basic (fig. 3.5) but affords a visible improvement in data quality (fig. 3.6). The most important actions within this flow are the removal of dominant low-frequency noise by bandpass filtering and the eradication of high angle noisy events by application of an f-k filter.

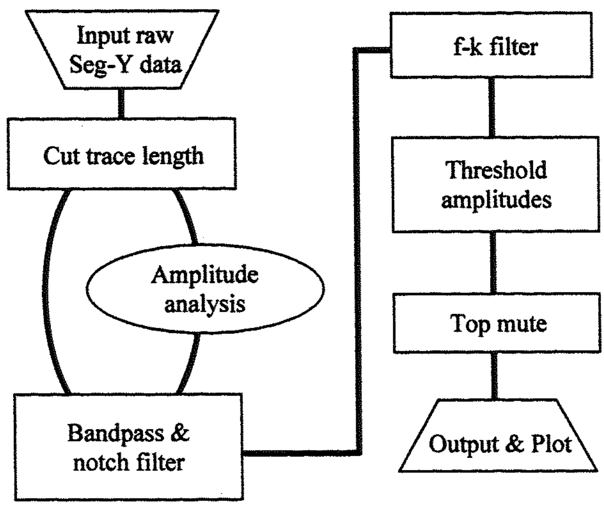


Fig. 3.5: Simple processing flow for Boomer data discussed within this volume. Trace length is reduced to speed processing execution time. Bandpassing is necessary to balance the spectral content of the return pulse, which is dominated by low frequencies (< 200 Hz). An f-k filter is applied to remove very high angle noise containing frequencies central to the signal bandwidth. Threshold amplitude and top mute are cosmetic applications aimed at clearing background "chatter" from the section for printing purposes.

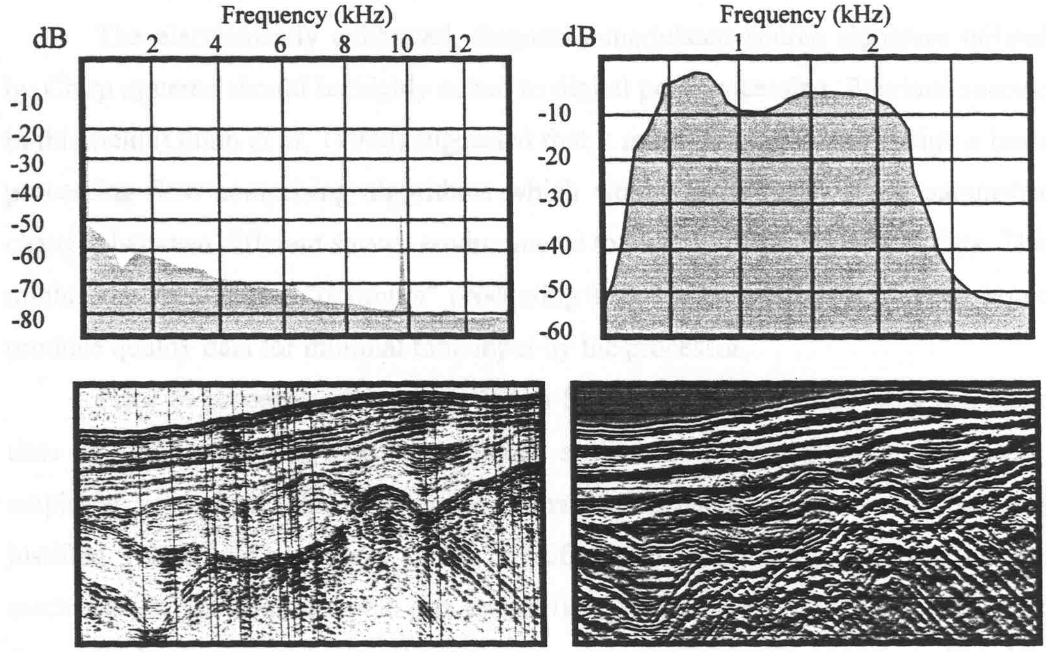


Fig. 3.6: Effect of simple post-processing on Boomer data. On the left is a section of data from northern Strangford Lough (see fig. 3.10 for location) and its corresponding mean frequency spectrum. This is seen to be dominated by low-frequency (< 200 Hz) noise. On the right is the same section after processing (but without amplitude threshold application). The frequency content is now more balanced, and improvement in the clarity of deeper reflections is notable.

Is laboratory-based post-processing of Boomer data worthwhile? The advantages of acquiring digital high-resolution seismic data outweigh those of analogue acquisition in several areas (Haynes *et al* 1993, Quinn *et al* 1998b): processing, display (2D/pseudo 3D) and quantitative investigation into reflector strength. In this study, the lack of a directly acquired source signature may have increased difficulties associated with post-processing, but spectral examination of the data suggests that Boomer source signatures are not perfectly repeatable and undergo rapid modification during passage through the water and sediment columns. The improvement in data quality arising through processing in ProMAX™ is small, and only a little better than that attainable on the shipboard Sonar Enhancement System. Results from Strangford Lough and elsewhere (Huws, pers. comm.) suggest that digital processing of Boomer data should be performed routinely, but only to a level sufficient to remove extraneous noise. The main advantage of using a mainstream seismic processing package is the facility to manipulate data for improved display, measurement, or attribute study.

The electronically calibrated, frequency-modulated source signature utilised by Chirp systems should be highly suited to digital post-processing. Previous success in this field (Quinn *et al*, 1998b) suggested that it might be possible to design a basic processing flow comprising algorithms which would require only small parametric changes between different survey environments to yield high quality output data. This might be considered an "optimum" processing flow for the system used, as it would produce quality data for minimal time input by the processor.

Prior to processing the entire, 85km Strangford Lough Chirp data set, some time was invested in attempting to create such a flow. Construction was largely empirical, beyond the initial basic premise that each processing step must be logically justified, robust and provide a visible, significant improvement in data clarity. The mechanics of the resultant post-processing flow (fig. 3.7) are presented in detail in Appendix I and summarised at this point. The robust nature of processing offered by following this short collection of ProMAX™ algorithms has since been proved by successful application to Chirp data sets from different regions, primarily by the author and subsequently by processors working on independent data sets.

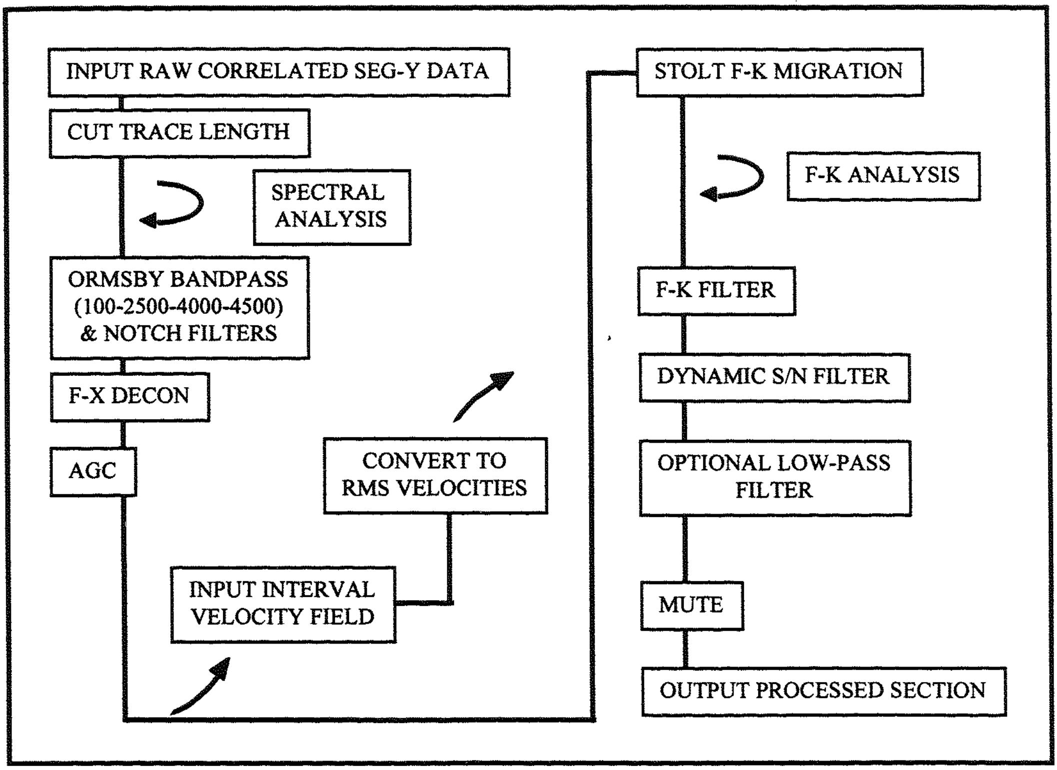


Fig. 3.7: Optimum post-processing flow for Chirp high-resolution sub-bottom data devised initially for rapid improvement of data acquired from Strangford Lough. A wider discussion of the processing steps employed is included as Appendix I.

3.5 Justification for a Dual-Instrumented High-resolution Seismic Survey

Acquisition of coincident multi-instrumented survey lines facilitates comparison between the sub-bottom profilers deployed. Previous comparisons of high-resolution profilers have discussed the source frequency content, directivity, etc. from a laboratory perspective (Verbeek, 1992). This approach may be technically exacting, but cannot be relied upon as a reliable indication as to the suitability and effectiveness of such tools in the true marine environment. In this chapter, the reflected pulse frequency content and overall data quality yielded by such systems are considered with respect to post-survey processing and interpretation.

The frequency content of typical laboratory-recorded GeoAcoustics™ Boomer and uncorrelated Chirp pulses is broadly similar (fig. 3.8). What is immediately apparent is the greater SNR and lower bandwidth of the Chirp pulse.

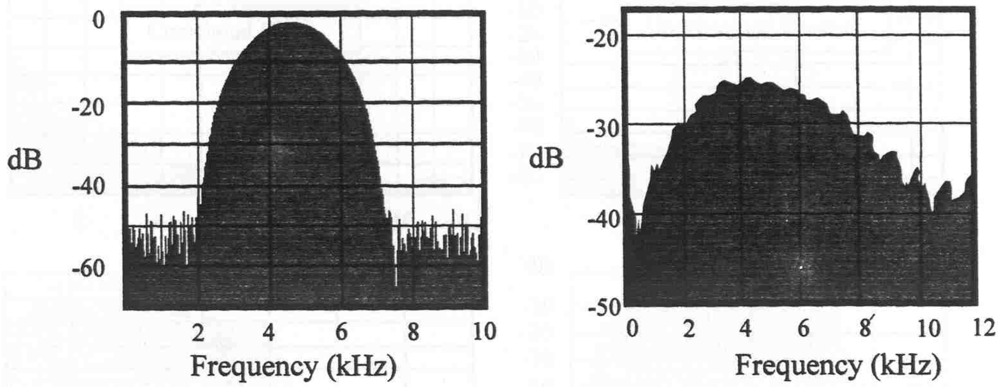


Fig. 3.8: Comparison of uncorrelated Chirp (left) and Boomer pulse discharge frequency content, recorded in a testing tank (Source: GeoAcoustics™). As might be expected, the Boomer pulse is of broader bandwidth, but much lower SNR. Significantly, at very low frequencies, noise from the Boomer increases, whilst the Chirp retains a high SNR. Problems experienced with low frequency noise during Chirp processing (Appendix I) appear therefore to be an artefact resulting from the default correlation sequence.

Comparison of these laboratory-derived spectra with actual reflection frequency spectra from sections through the late- and post-glacial sediments of northern Strangford Lough demonstrates that the practical bandwidth of the systems is greatly reduced, even at the top of the sediment column (fig. 3.9). Both sources suffer dominance by low (< 200 Hz) frequency noise, which is removed by bandpass filtering. The source of this noise is undetermined for Boomer data, but in the case of the Chirp, noise-free uncorrelated records suggest that Instantaneous Amplitude conversion (Appendix I) during the correlation sequence may be responsible.

Comparison of the signal bandwidth for reflected Chirp and Boomer pulses (fig 3.9) (overleaf) demonstrates the advantages of a controlled, calibrated electronic source. The useful reflected pulse signal bandwidth for the Chirp is 4.5 kHz, whilst that of the Boomer has been cut to c. 2 kHz. The immediate consequence of this is apparent both in seismic section (fig. 3.10) and by calculation of theoretical vertical data resolution: Chirp resolution is approximately 0.35m, compared to calculations[2] of between 0.52 and 0.80m for the reflected Boomer pulse.

[2] Vertical resolution values for the reflected Boomer pulse are calculated for the dominant frequency (c. 750 Hz) and signal bandwidth (2 kHz) respectively, at the velocity of 1575 ms^{-1}. The methodology and values adopted are discussed in Appendix I: *Post-processing of Digital Marine Chirp Data.*

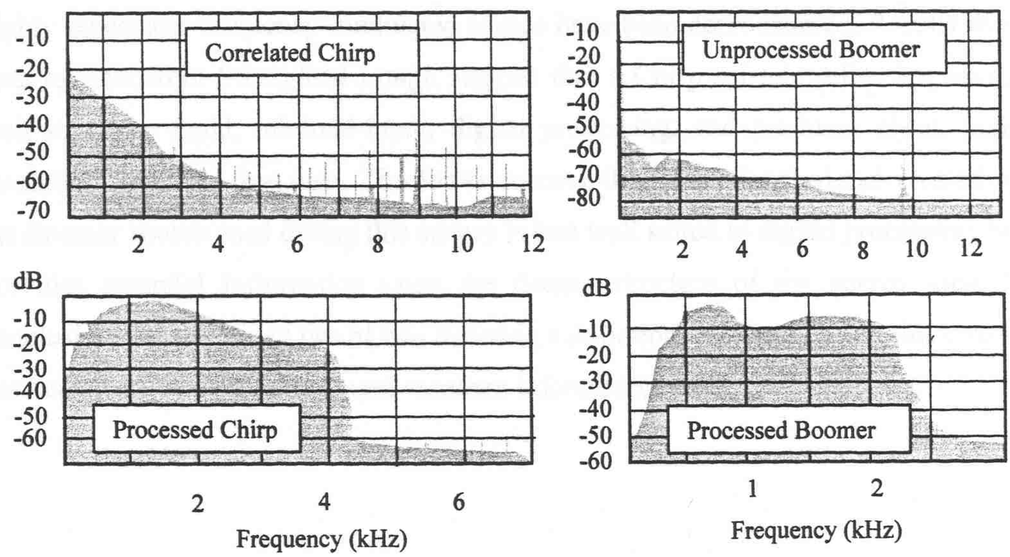
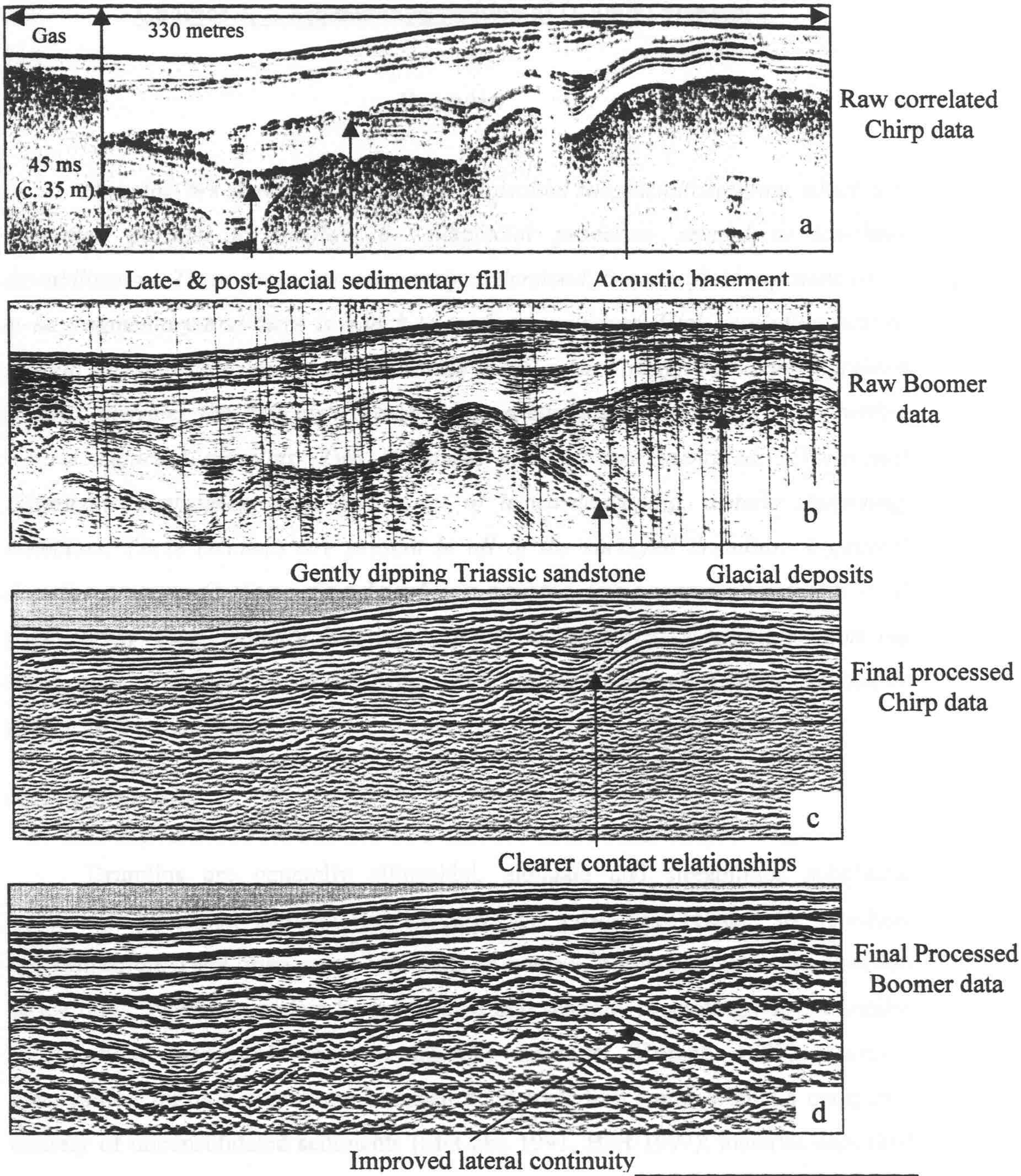


Fig. 3.9: Reflected pulse frequency spectra for a Chirp (left) and Boomer (right) source, at the acquisition (top) and fully post-processed (bottom) stages. Spectra have been calculated in ProMAX™ from identical time windows at points of close survey track coincidence in northern Strangford Lough.

Spectral analysis shows that bandwidth preservation of the Boomer pulse is poor by comparison to Chirp. This is apparent in figure 3.10, where multiple suppression resulting from matched filtering during the default Chirp correlation sequence is also demonstrated. Attempts to suppress peg-leg and bottom multiples during boomer processing were only partially successful, as lateral variability in reflector characteristics required continual changes in the prediction filter, rendering the process highly inefficient. In the same sections, the major advantage of using a Boomer source is exemplified by clear images of dipping reflectors beneath the Chirp acoustic basement, which have been interpreted as representing Triassic sandstone.

This discussion may seem somewhat unnecessary - beyond the need to consider source resolution - given the popular conception that Boomers will generally provide higher penetration than Chirp profilers, at the expense of resolution. This appears to be the first time that two systems supplied by a leading manufacturer have been directly compared at all stages of operation, by an end-user with commercial processing software at their disposal. Results obtained from Strangford Lough suggest that, despite similar output source frequencies, Chirp and Boomer can fulfil very different, complementary purposes in high-resolution surveying. It has been suggested (Darling 1999) that improvements to modern Boomer sources have rendered the use of Chirp systems unnecessary. In this chapter, the advantages of using a controlled, highly repeatable frequency-modulated source have been demonstrated. Results from tests on data from Strangford Lough suggest that a Chirp seismic reflection data is well suited to rapid, minimal-input, digital processing, and produces clean, high-resolution, multiple-free data. The lower repeatability, directional signal created by the Boomer source used during this survey is less well suited to digital processing, but provides essential information upon the deeper structure of the survey area. In conclusion, the combined use of two differing sub-bottom profilers during this project has been justified by the increased resultant information yield.



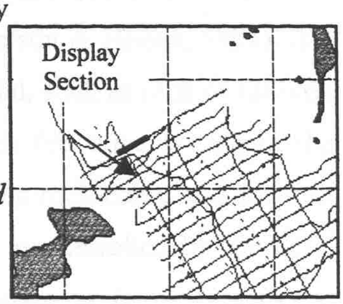


Fig 3.10: Comparison of Chirp (a,c) and Boomer (b,d) data from near-identical survey lines in northern Strangford Lough (right). In this example, the most obvious contrasts lie in section resolution, the presence of peg-leg multiples in both unprocessed (b) and processed (d) Boomer data, and the superior penetration of the Boomer source.

Chapter 4: A Seismic Investigation of Drumlin Structure

Overview

Drumlins are streamlined, elongate ellipsoidal subglacial bedforms, which are generated parallel to ice-flow by subglacial processes related to ice-sheet destabilisation. These processes are poorly understood, because field exposure tends to be fragmentary and there is a lack of modern analogues. High-resolution marine seismic surveying of submerged and buried drumlins in Strangford Lough, Northern Ireland, provides the first clear evidence for a consistent internal structure within several adjacent drumlins. Two structural elements are identified: a proximal seismically transparent zone and a set of leewards-dipping, distally steepening reflectors. These elements are present in all of the surveyed drumlins. A general drumlin structure for Strangford Lough is suggested, using measurements extracted from survey data. Drumlin location is found to exhibit a dependency upon the topography of the underlying substrate, which can be composed of either bedrock or unconsolidated sediment.

4.1: Introduction

Drumlins are generally ellipsoidal, elongate and streamlined subglacial bedforms, generated parallel to ice-flow by processes related to ice-sheet destabilisation. They often group into belts or *swarms*, perpendicular to the direction of ice flow. Swarms can often be subdivided into spatially separate groups of similar composition, form and apparent internal structure (Knight, 1997). Drumlin composition forms a continuum between solid rock forms and drumlins composed entirely of unconsolidated sediments (McCabe 1991, Hart 1997); material deposited within drumlins is generally rich in sand and gravel (Patterson & Hooke, 1995). If a drumlin is situated above a zone of more competent material, such as rock or till with greater shear strength than the overlying diamicton, then this zone is termed the drumlin *core* (fig. 4.1). Knight (1997) distinguishes between rock-cored and diamict-dominated drumlins. The shape of a rock-cored drumlin is controlled by the core, which is overlain by a thin and discontinuous diamict carapace, up to a few metres in thickness, whereas diamict-dominated drumlins may contain a rock core, but over 80% of the observed sequence comprises subglacial diamict and other sediments.

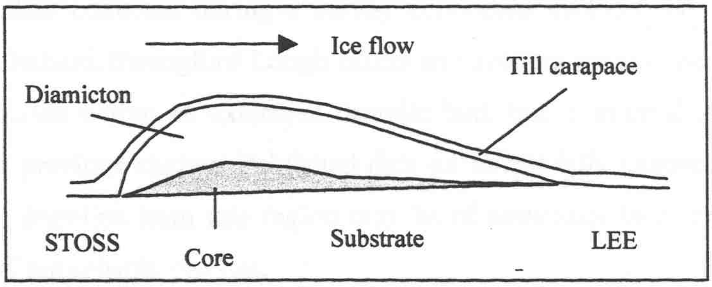


Fig. 4.1: General structural terminology for a "classic" shaped drumlin cored by more competent material.

Large numbers of drumlins are reported from ice-marginal locations, and it has been suggested that the majority of drumlin fields form in association with radially divergent flow conditions beneath relatively thin (200-1000m) ice (Vernon 1966, Patterson & Hooke 1995). Observations by Clark (1994, 1999) suggest that drumlinisation can occur in non-marginal locations as a result of different environmental conditions and active processes.

There are no known modern analogues to drumlin formation. The processes determining the composition and structure of drumlins remain undetermined, despite a century of study, which has produced numerous competing hypotheses (Menzies 1989a, Clark 1999). The drumlin problem can be deconstructed into three elements: how and why sediment arrives at the site, how a particular internal structure is developed, and by what means the final streamlined form is produced. Formational hypotheses are often site-specific and do not correlate well between areas, due to subjective interpretation of frequently ambiguous data. Subjectivity in observation also results from a lack of statistically robust, accurate measurements of drumlin internal structure across individual swarms. Such measurements have previously only been obtained in a scattered, penetrative (often destructive) and relatively opportunistic fashion affording limited perspectives upon the true nature of the deposit (Rose, 1989).

Marine reflection seismology has the potential to determine drumlin internal structure, although previous attempts (e.g. Oldale *et al* 1994, Davies *et al* 1997, Fader *et al* 1997) have not fully demonstrated this. The advantage of this technique lies in the ability to produce rapid, continuous profiles through buried geological structures, overcoming the problems posed by poor or non-existent terrestrial exposure. This chapter considers the application of high-resolution marine surveying to the "drumlin problem", using data collected during a survey conducted in 1997, on Strangford Lough, Northern Ireland. Strangford Lough offers an excellent environment for such work, as it is situated within an extensive drumlin belt, but is more sheltered than areas surveyed in previous studies. Published data on terrestrially exposed, spatially contemporaneous drumlins from this region may be of assistance in correlation and ground-truthing of the seismic profiles.

4.2: Drumlin Classification by External Form

It has been suggested (Smalley & Warburton, 1994), that classification of external form may represent a key element in the determination of formational processes. Drumlin shape is quantitatively described through drumlin length, axial ratio, eccentricity, external surface curvature, and derivatives of these properties (Vernon 1971, Evans 1987). Drumlins typically range from 30m to 2km in length, and vary gradually in size across swarms (Vernon 1966, 1971). Uncertainties concerning formational process render such limits effectively arbitrary, as the demarcation of a drumlin lee end can only sensibly be regarded as being represented by the stoss end of the following drumlin. Axial ratios from 1:1 to 13:1 and averaging 2:1 to 3.5:1 have been recorded in Ireland (Vernon, 1966), with topographic expressions of 5 to 50 metres above the surrounding till or rock surface (Ritter *et al*, 1995).

Alternatively, drumlins can be divided into descriptive groups, e.g. the *spindle, parabolic and transverse asymmetrical drumlins* described by Shaw *et al* (1989) (fig 4.2).

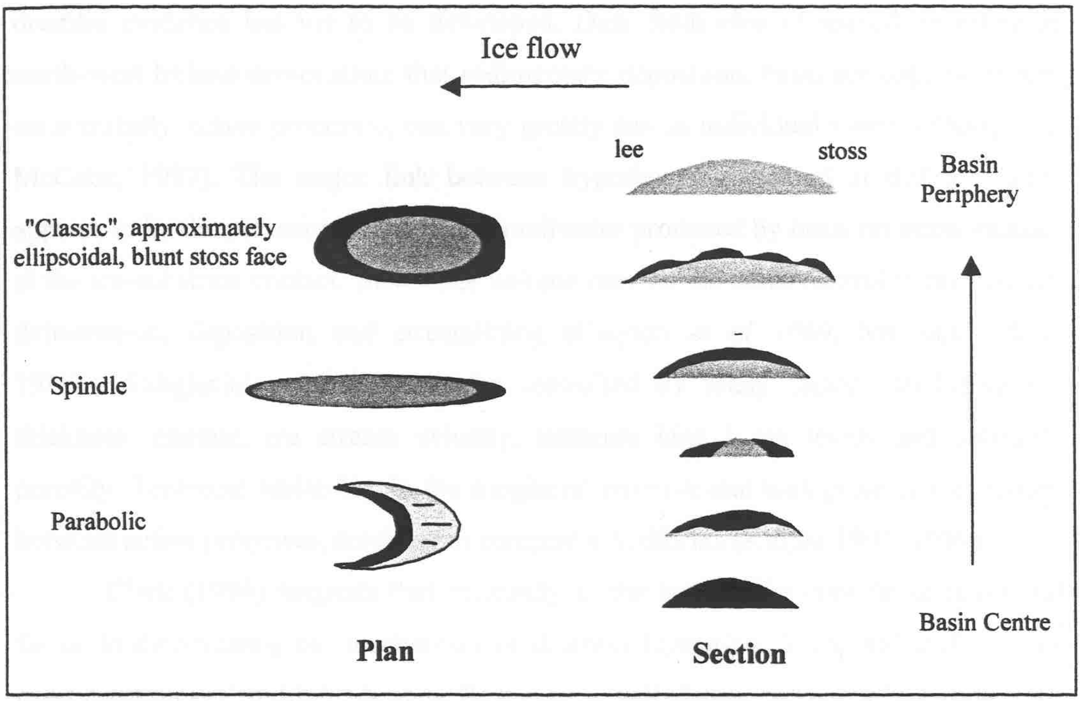


Fig.4.2: Examples of drumlin form. The classic drumlin form is that of an ellipsoid with a blunt stoss face (top left). Spindle and parabolic drumlins are common in areas affected by the Laurentide ice sheet (Shaw et al, 1989). Drumlins in northern Ireland form a sequence ranging from streamlined rock masses (top) to till drumlins superimposed upon unconsolidated sediments (after McCabe, 1991).

Isolated study of external form cannot explain drumlin formation, as similar forms appear to result from differing formational processes. A study of the internal structure of a large number of drumlins appears imperative to the understanding of formational processes, but has largely been thwarted by the lack of available continuous geological exposure.

4.3: Hypotheses for Drumlin Formation

McCabe (1991) sums up the difficulties involved in process investigation, pointing out that drumlins cannot be readily observed *in statu nascendi*. Boulton & Hindmarsh (1987) suggest that the majority of modern glaciers overlie solid strata, whereas during the last glacial, a large percentage of the ice sheets would have lain upon unconsolidated material. During the decay of the major ice sheets there existed a glaciological and climatic situation for which there is no known modern analogue.

A global theory successfully encompassing explanation of all published drumlin evidence has yet to be developed. Data from closely spaced drumlins in north-west Ireland demonstrate that sedimentary deposition, basal ice conditions and consequently, active processes, can vary greatly across individual swarms (Knight & McCabe, 1997). The major link between hypotheses generated at different sites appears to be the presence of subglacial meltwater produced by basal pressure melting at the ice-substrate contact. Meltwater volume may be the main control upon erosion, deformation, deposition and streamlining (Clayton *et al* 1989, Menzies 1989a, 1989b). Subglacial processes may be controlled by many factors, including ice thickness, climate, ice stream velocity, terminal lake / sea levels and substrate porosity. Temporal variability in the subglacial environment may produce fluctuation between active processes, resulting in composite bedforms (Knight 1997, 1999).

Clark (1994) suggests that proximity to the ice margin may be an important factor in determining the mechanism of drumlin formation. Temporal shifts in ice mass position and multiple, discrete flow events, will change the prevailing conditions and facilitate reworking of deposits in differing environments and orientations (Knight & McCabe 1997, McCabe *et al*, 1999). Modern valley glaciers exhibit progression from hydraulic throughflow to fluvial channelising during the melt season, implying that deformational processes are replaced by fluvial erosion and deposition with time (Hart, 1995). This recent acknowledgement of the possible spatial dynamism and duration of the drumlinisation process is facilitating the integration of previously incompatible theories for drumlinisation, which fall into four general groups:

(1) Drumlins are formed by glacial erosion of pre-existing sediments (Hart, 1997).

(2) Drumlins are formed by glaciofluvial action during a single catastrophic outward release of meltwater from the ice sheet interior (Shaw *et al* 1989, Shaw 1994).

(3) Drumlins are formed by lee-side saturated sediment flows and fluvial deposition, which occurs within cavities in the lee of pre-existing obstructions to ice flow (Dardis *et al* 1984, Hanvey 1989, Dardis & Hanvey 1994).

(4) Saturated subglacial sediment is moulded, deformed and preferentially preserved about erosion-resistant basal sediment volumes as drumlins (e.g. Menzies 1977, Boulton 1996, Hart 1995).

Some hypotheses attempt global explanation of drumlin field development, whilst others explain only localised deposits or perceived individual processes within the overall formational process (Ritter *et al*, 1995). The simplest drumlin forms are those eroded from pre-existing sediment **(1)**. These drumlins may be thinly draped by a melt-out till carapace, which is unrelated to their internal structure. The main bodies of such drumlins are composed from either homogenous till with a down-flow clast orientation, or from truncated stratified material, either of which are more resistant to glacial erosion than the surrounding material. The sedimentary body of such a drumlin comprises material shielded and preserved by the presence of this obstruction.

Some formational hypotheses seek only to explain formation specific drumlin types, e.g. the Laurentide meltwater hypothesis **(2)**(Shaw *et al* 1989, Shaw 1994). This hypothesis proposes drumlin formation by subglacial meltwater surge, creating both *depositional* drumlins containing stratified deposits, and *erosional* drumlins consisting of bare bedrock ridges surrounded by fluvial scours (Menzies 1989a, Shaw *et al* 1989). Scouring is attributed to the erosional action of horseshoe vortices within fast-flowing meltwater, whilst fluvial sequences were deposited in basal, hydraulically eroded ice cavities (Shaw *et al*, 1989). Synchronous cavitation by a single continuous sheet of subglacial meltwater, is envisaged, prior to cavity-fill sediment deposition resulting from falling hydraulic competence. Smooth transition in external form across drumlin swarms implies simultaneous formation by a meltwater flood as wide as the swarm itself. A single floodwater release event of estimated volume sufficient to raise eustatic sea level by 23cm is suggested (Shaw, 1989). This estimate arises from analogy to modern hydraulic bedforms, (e.g. ripples), which undergo total submersion during formation. Depositional drumlins proposed to have formed in this manner include the spindle and parabolic forms (fig. 4.2), which are subsequently covered by a thin veneer of melt-out till (Shaw *et al*, 1989).

The potential subjectivity of observations based upon relict deposits is demonstrated by Eyles & Boyce (1998), who refute the catastrophic subglacial flood hypothesis, following field re-examination of the supporting evidence. This interpretation concludes that deposits at the type locality predate the overriding ice sheet and do not indicate the presence of catastrophic meltwater floods.

A second theory of cavitational drumlin formation describes repeated emplacement of saturated sediment into a subglacial vein-cavity network, located to the lee side of obstructions upon the ice-substrate contact **(3)** (Dardis *et al* 1984, Dardis & Hanvey 1994). This type of drumlin typically exhibits a series of stratified sands and stratified gravels forming a lee-side deposit behind a main body of unstratified diamict. Repetitive coupling and uncoupling of the ice sheet and basal substrate might produce a sequence of alternating tills and stratified deposits containing a range of sedimentary and deformational structures. Drumlin-crest fluvial deposits described from NW Ireland (Dardis & Hanvey, 1994) have been interpreted as representing total uncoupling of the ice sheet, subsequent to lee-side deposition. This implies major subglacial water release, similar to that proposed for the Laurentide ice sheet (**2**); it is also suggested that decoupling may provide the mechanism for glacial surges and streamlining. Knight (1997) describes similar fluvial deposits from drumlin crests in Omagh, suggesting that in this case, volumes of meltwater sufficient to submerge the drumlin crest were present at a point following deposition of the main body of sediment.

The presence of a soft, deformable layer of material at the ice-substrate contact beneath contemporary ice streams in Antarctica has been demonstrated from seismic evidence (Blankenship *et al* 1987, Rooney *et al* 1987, Alley *et al* 1987) and by direct measurement (Boulton & Hindmarsh, 1987). Subglacial glaciotectonic deformation hypotheses **(4)** (Hart 1995, Boulton 1996, Hindmarsh 1997*),* invoke the erosion, deposition and deformation of a layer of deformable subglacial sediment undergoing periodic coupling with the glacier bed. Meltwater volumes produced by pressure melting are unable to escape rapidly, producing excess pore pressures and facilitating deformation (Hart, 1995). The exact mechanisms and scale of deformation within this layer has not been fully established; Hindmarsh (1997) reviews important ideas and demonstrates the continuum between fluid (fluvial) movement of material and deformation at lower saturation. Menzies (1989b) proposes that the hydraulic conductivity of this layer and of the underlying strata will determine whether uncoupling and glacio-fluvial processes, or deformation, will occur. Three classes of layer composition are proposed: H (hard), Q (intermediate) and M (deformable) (fig. 4.3), exhibiting differing rheological response to applied stress as a function of shear strength, rigidity, porosity and permeability.

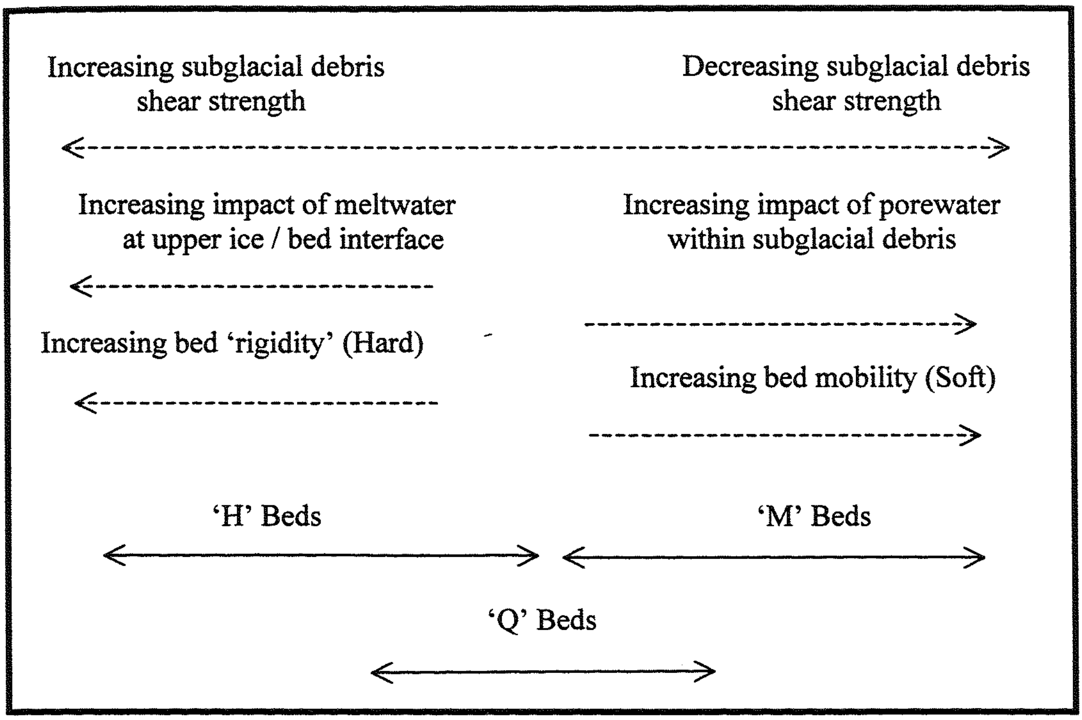


Fig. 4.3: Classification of proposed subglacial temperate bed types, after Menzies (1989b). The contrast in porosity and permeability of the basal layer and underlying strata are thought to govern the active physical process. Deformation is likely if 'M' bed sediments are present.

Uncoupling of the ice sheet, resulting in predominantly hydraulic formation processes is likely in the case of 'H' beds subjected to negative effective stresses as a function of increased pore pressures. 'M' beds attain a slurry-like consistency, allowing deformation and rapid down-flow transfer of material as saturated debris flows under such conditions. 'Q' beds are likely to be the most important layer type, as they reflect the probable interaction of deformation and uncoupling resulting from frequently fluctuating basal porosity and pore pressure beneath ice sheets.

Deforming layer thickness is crucial to the argument supporting deformational drumlinisation. Menzies (1989b) estimates a typical value of <10m for the deforming (M) bed situation. In this model, drumlin formation is thought to result from perturbation at the lower boundary of the deforming horizon, triggering net subglacial deposition and localised thickening of the sediment layer. Boulton (1996) suggests that glacial forms on the ice margins will be mostly depositional, whilst those more proximal to the divide at the centre of the ice sheet should be erosional. Beneath the ice divide, preservation of material without deformation is envisaged. McCabe (1991) notes a similar graduation in form across glacial deposits from the northern Irish

Midlandian.

It is possible that the volume of subglacial meltwater present may link some or all of the hypotheses detailed above, in a continuum of formational process. The existence of such a continuum between erosion, deformation and lee-side deposition during drumlinisation has previously been proposed by McCabe (1991), Boulton (1996) and Hart (1997). The parameters controlling fluctuation between erosional, depositional and deformational processes are currently insufficiently defined. Ambiguity arising from field exposure hinders elucidation of these parameters and will also affect ground-truthing of high-resolution seismic data. Consequently, it may not yet be possible to seismically determine the process responsible for drumlin formation, although such an approach should provide a rapid and objective method for establishing cross-swarm variability in drumlin structure.

4.4: Drumlin Distribution and Triggering

The least accessible area of the drumlin bedform is the basal contact with the underlying substrate. Mapping of this horizon is crucial to establishing whether drumlin distribution is a function of substrate, deforming layer or basal ice properties. It is generally accepted that a perturbation of flow is necessary to initiate drumlinisation, but whether the source of perturbation is mobile or static is uncertain.

Patterson & Hooke (1995) suggest that any obstruction upon the basal substrate may be sufficient to excite ice flow instability and allow drumlin growth by erosion around the obstruction, deposition over it, or both. The same authors suggest that drumlins formed in this manner might not form above the immediate location of the obstacle, but could be created downflow by perturbation of the basal ice or deformable layer. Such obstacles include large boulders, either in-situ or transported and rendered static as a consequence of "ploughing" into the substrate (Hart, 1995). However, the presence of large boulders without associated drumlin deposits within drumlin swarms (Patterson & Hooke, 1995) suggests that the mere presence of an obstacle may be insufficient to initiate and maintain drumlinisation. Gravity profiles presented by Raukas & Tavast (1994) clearly suggest that underlying bedrock topography may in many cases be responsible for drumlin location. Drumlins exhibiting lee-side stratification sequences (e.g. Hanvey, 1987, 1989) are postulated to form behind pre-existing obstructions to ice flow, located upon the upper surface of the substrate. Knight (1997) suggests that erosion of pre-existing strata prior to subsequent deposition of material is part of the drumlinisation process in Omagh.

An alternative to drumlin initialisation by static obstacles is nucleation of more competent material close to the base of the deforming layer, followed by growth resulting from associated deposition (Menzies 1977, Menzies 1989b, Rose 1989, Hart 1995). Such a nucleus might be created by accumulation of boulders, localised freezing, or by concentration of coarser grained material. Menzies (1989b) suggests that the resultant core will be mobile, rendering the search for triggering mechanisms beneath deformational drumlins unsuccessful. The circumstances responsible for nucleation demand consideration; the reason for accumulation of boulders or coarse sediment may be as important to drumlinisation as the proposed ensuing process of sediment deposition.

4.5: The Applicability of Marine Seismology to Drumlin Investigation

Field mapping provides essential information on the physical composition of drumlins, but provides only fragmentary data upon their internal structure. Other methods employed in attempting to overcome this information gap include aerial photography (Clark 1994, McCabe & Clark 1998), numerical modelling (Smalley & Warburton, 1994), and the application of geophysical techniques (Oldale *et al* 1994, Davies *et al* 1997, Fader *et al* 1997). Gravity surveys over drumlins (Raukas & Tavast, 1994) suggest that bedrock topography is a major factor in drumlin location, although the gravity method cannot determine the possible controls exerted by buried palaeomorphologies lying above the bedrock surface.

It seems likely that no single approach to the problem will succeed in isolation; geophysical data requires ground truthing by field geologists, field data lacks continuity of exposure, aerial photography is largely two-dimensional and numerical modelling of subglacial deformation requires field data for parameter control. High-resolution marine seismology may provide a link between the other approaches by virtue of the continuity of the three dimensional information which such surveys can afford. In particular, it can provide information on the broad internal structure of drumlins and the nature of the drumlin - substrate relationship, which is possibly of great significance and has previously been extremely difficult to study by traditional methods.

4.6: The Glacial Deposits of Strangford Lough

The most recent cold stage in Ireland has traditionally been termed the Midlandian and is regarded as being equivalent to the British Devensian. The glacial history of late Quaternary Ireland is still contentious (Ehlers *et al*, 1991 - p68) and the number, timing and extent of the Midlandian ice masses has not yet been satisfactorily constrained (Hoare 1991, Warren 1991). Recent work on north-east Ireland (McCabe & Clark 1998, Knight 1999, McCabe *et al* 1999) has utilised AMS ^{14}C dating and remote-sensing imagery to resolve and chronologically constrain individual events and shifts of ice-mass centre during the late Midlandian. It has been suggested (Knight, 1999) that previous studies produced over-simplified models which are not compatible with recently published information and do not reflect the complexity of Irish subglacial bedform patterns.

Strangford Lough lies 8km from the north-eastern end of a 150km long drumlin belt (McCabe & Dardis 1989, fig 1). There are examples of rock-cored drumlins exposed nearby Strangford Lough; other drumlins in this area are diamict-dominated drumlins cored by a lower, earlier till unit. Drumlin formation in north-east Ireland occurred during a series of millennial-scale ice-sheet oscillations between c. 19000 and 14500 BP (McCabe 1996, McCabe & Clark 1998, Knight 1999), only two of which (stages A & C) are significant to this study of Strangford Lough. Bedform patterns suggest that Strangford Lough was initially affected by Irish Sea Ice flowing NE-SW (*Flow stage A* - McCabe *et al*, 1999)(fig. 4.4), and subsequently by ice from the main Irish ice mass moving approximately NNW-SSE (*Flow stage C*). McCabe *et al* (1999) dated the initial event (A) to before 25000 yrs BP. During this event, ice from a major ice centre in SW Scotland (c. 250km to the NE) pushed approximately 60km inland. Whether this phase deposited a distinct, extensive unit of till (Hill 1968, Hill & Prior 1968) is not certain; more recent studies (McCabe, pers. comm.) have failed to find such a layer. This layer is termed the "lower" till by those subscribing to its presence; this terminology is retained here in the absence of published evidence against its existence. Flow stage C (17000-16500 BP) deposited a widespread till unit across the Strangford Lough region (the "upper" till of Hill (1968)) and effected drumlinisation across the area (fig. 4.3).

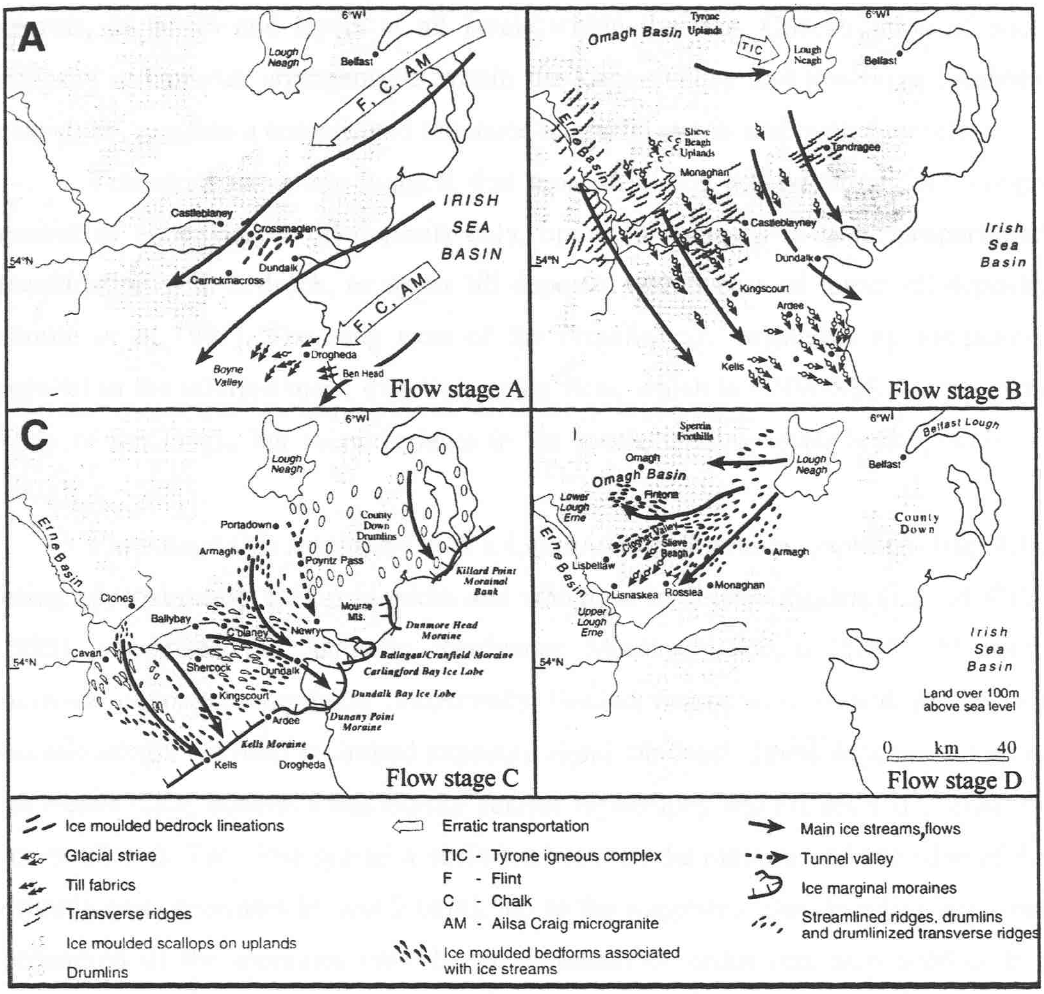


Fig. 4.4: Summary sketch of ice flow patterns and field evidence used to establish the ice flow stages described by McCabe et al, 1999. (Reproduced from McCabe et al, 1999.) Remote sensing data studied independently (Clark, pers comm.) broadly supports the relative chronology and flow directions suggested for Strangford Lough, although detailed studies of this area (e.g. Vernon, 1971) provide more specific information.

The axis of flow stage C lay between Lough Neagh and the North Channel (Smith *et al* 1991, McCabe *et al*, 1999). The ("upper") till deposited during this event has a reported thickness of 1-13m in East Down and South Antrim (Hill & Prior, 1968), but is highly variable and may exceed these values. Drumlins formed within the upper till have a predominantly north-west to south-east orientation, although this varies between north-south and east-west across the drumlin belt within Co. Down (Vernon, 1971). The upper till contains only small amounts of erratic material and is seen to rest upon both bedrock and lower till deposits (Smith *et al*, 1991). Hill (1968) observed that in topographic depressions within the Lagan valley (c. 10-15km NW of Strangford Lough) the upper till occurs in association with fluvio-glacial sands and gravels, in lenses and layers at all levels within the unit. Concentration of such deposits in complex arrangements within the Lagan valley and low-lying localities elsewhere, suggests a complicated sequence of glacial events and meltwater release.

Terrestrial exposures suggest that most drumlins around Strangford Lough consist of either: upper till deposits only, upper till deposits in some proportional combination with bedrock, or upper till deposits with a core of lower till deposits (Smith *et al* 1991). The long axes of the drumlins are orientated approximately parallel to the inferred mean direction of ice flow, which is NNW-SSE for the main body of the lough, but more variable in the south, tending towards N-S (Vernon, 1971).

Flow stage C is associated with a 130km series of terminal moraines (fig. 4.4), being approximately 1-3km in width and which, in traditional models (e.g. McCabe 1993), comprised the "Drumlin Readvance Moraine" (Knight, 1999). Morainic outwash deposits comprising horizontally bedded coarse gravels and sands, and occasional till, are seen in limited exposure along the coast. These deposits are up to 20 metres thick, possess a hummocky surface topography and are seen to overlie the lower till unit. The close spatial association between the moraine and the edge of the drumlin belt (separated by just 2-6km), led to the suggestion that drumlinisation and deposition of the moraines must be pene-contemporaneous and associated with a major ice re-advance (Hill 1970, Synge 1970). McCabe *et al* (1999) (fig. 4.4) demonstrate that this moraine resulted from just one of a series of late-stage deglacial oscillations rather than a single synchronous final ice mass advance ("*The Drumlin Readvance*"). Chronographic limits for this event have been established from AMS ^{14}C dating of coastal marine muds at Killard Point, Cooley Point and Rough Island in Strangford Lough (McCabe 1996, McCabe & Clark 1998). This mud forms a regional drape (see chapter 5) overlying drumlinised till, and indicates that flow stage C was probably closely related to rising sea levels and tidewater evacuation into the Irish Sea basin (Eyles & McCabe 1989, McCabe *et al* 1999).

4.7: Survey Results

The acquisition and processing of data collected to support this study are described elsewhere (Chapter 2, 3 & Appendix I). Twenty-nine kilometres of boomer data was acquired (fig. 4.5) during the survey. In the northern grid the survey was enhanced by the addition of 85km of superimposed and intermediate parallel GeoAcoustics GeoChirp sub bottom profiles (1-8 kHz. & 15cm vertical resolution) and 100 kHz side scan coverage, at 150 metre line spacing. Both sub-bottom profilers were mounted upon towed catamarans, which facilitated their operation in shallow water. A real-time positioning accuracy of ± 1m was achieved using differential GPS, whilst tidal variation was monitored on a shore-based gauge. Ship speed during data acquisition was c.5.5km / hour and sea conditions were calm.

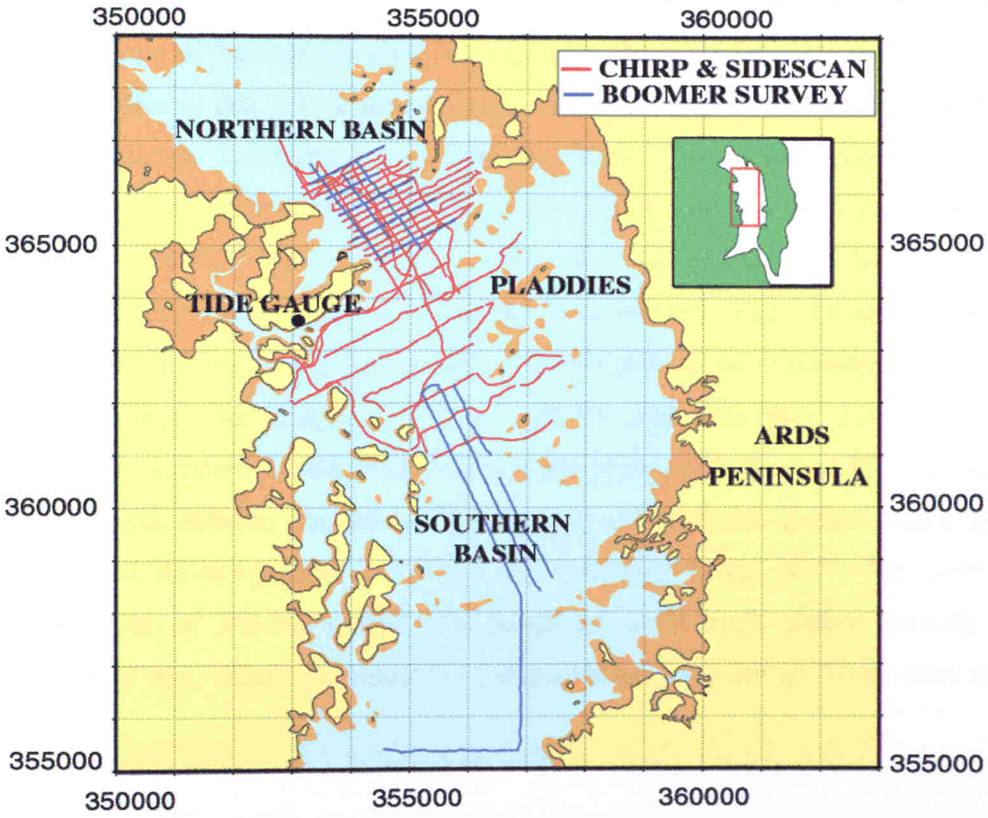


Fig. 4.5: Seismic survey coverage of 1997, described in this chapter. Drumlins have been surveyed approximately along the axis of the lough, but the presence of shallow gas deposits in data from the northern grid makes this area less suitable for study.

4.8: General Distribution of Submarine Deposits

On the basis of seismic character, it is possible to broadly divide the seismic data into three groups of deposits, the lowest of which contains extensive reflectors whose continuity and dip correlates with Triassic Sherwood Sandstones mapped onshore (GSNI sheet 37 & 38, Smith *et al* 1991). Immediately above this is a region of chaotic reflectance suggestive of unstructured sediments and inferred to represent glacial diamict, whilst above this, the uppermost deposits exhibit seismic stratification suggestive of marine or lacustrine deposition.

Zones of high acoustic reflectance, stepping through horizons within the sediment drape, are common in the northern survey area, yet absent in the south. These reflectors are interpreted as representing shallow gas. Shallow gas at even very low concentrations is impenetrable to high frequency sources (Anderson & Bryant 1989, Judd & Hovland 1992), thus data from the northern area yields less information on the structure of the bedrock and glacial deposits than that from the south. Boomer data also indicates that glacial morphologies differ between the central and northern parts of the lough. The southern area exhibits variable, but generally thick (15-80m) deposits of glacial sediments, whilst to the north, these deposits form a sheet which has infilled bedrock depressions to a depth of c. -60 metres OD, but otherwise maintains a thickness of less than ten metres over bedrock. Thus the southern area, with its absence of gas, and deeper water, provides the focus for this study.

The large-scale bathymetry of the northern grid area (figs. 3.2 & 4.10) is controlled by a buried palaeochannel cut into the bedrock plateau and filled by up to 30m of diamict. Seismic lines 401 to 405 (fig. 4.6) cross-cut this channel, whilst lines 406 and 408 lie sub-parallel to it. The palaeochannel trends NW - SE, with an apparent width of 300-500 metres. The height of the bedrock plateau beneath the northern grid is c. -22m OD, whilst the palaeochannel base lies at -70 to -80m OD.

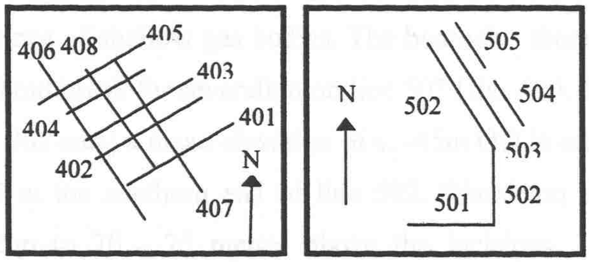


Fig.4.6: Boomer survey grids containing names for lines discussed in the following section. Refer to fig. 4.5 (previous page) for geographic setting.

Boomer, Chirp and side scan images of the northern area contain elongate topographic highs, which are partially visible between the shallow gas zones. Continuous gas-free sections are rare in the northern section though, and only one such feature, (48A) has been accurately measured, on line 408.

Evidence supporting the active erosion of glacial morphologies in shallow waters is observed both on line 401, and also on the corresponding Chirp and side scan sonar lines (fig. 4.7). Post-glacial relative sea level around the coast of North-east Ireland fell to a minimum of c.-20m OD around 9000 years BP (see following chapter), before rising rapidly to a maximum of +3m OD at c.6000 yrs BP (Carter, 1982). Erosion of glacial deposits is therefore likely to depths of c. -20m OD.

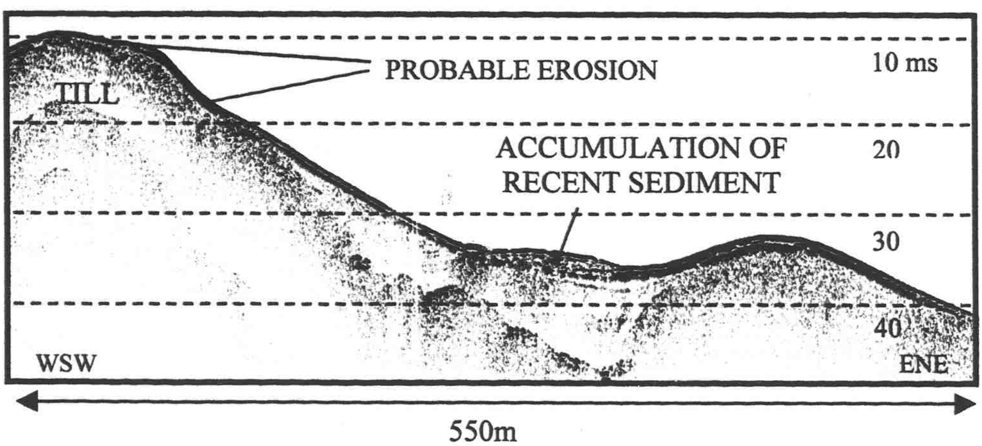


Fig. 4.7: Chirp seismic evidence for active erosion of glacial deposits in north-west Strangford Lough. Truncation of rounded drumlin tops to form flat-topped reefs known locally as Pladdies is commonly observed within the inter-tidal zone. Seismic data indicates that erosion of glacial deposits is likely to occur at depths of c. -20m OD (see following chapter), so only structures located within the deepest regions of the lough are likely to be well preserved. Data presented in this chapter was acquired at depths generally greater than -30m OD.

Lateral continuity in the southern grid is superior to that of the northern, due to an apparent absence of shallow gas bodies. The bedrock - diamicton relationship can be followed without break for severalkm on line 502 (fig. 4.6). Bedrock topography is more diverse in this area; a mean elevation of c. -45m OD is incised to a depth of c. -75 to -85m OD at the southern end of line 502. Diamicton thickness ranges from approximately 5m to 70 - 75 metres above the incisions. Late- and post-glacial sediment thickness is also greater (up to 7-10m) in the southern basin.

4.9: Identification of submerged and buried topographic highs

Elongate topographic highs have been identified in seismic section, located within the glacial deposits and below the -30m isobath. These features have a mean apparent length, parallel to seismic profile, of 483m.

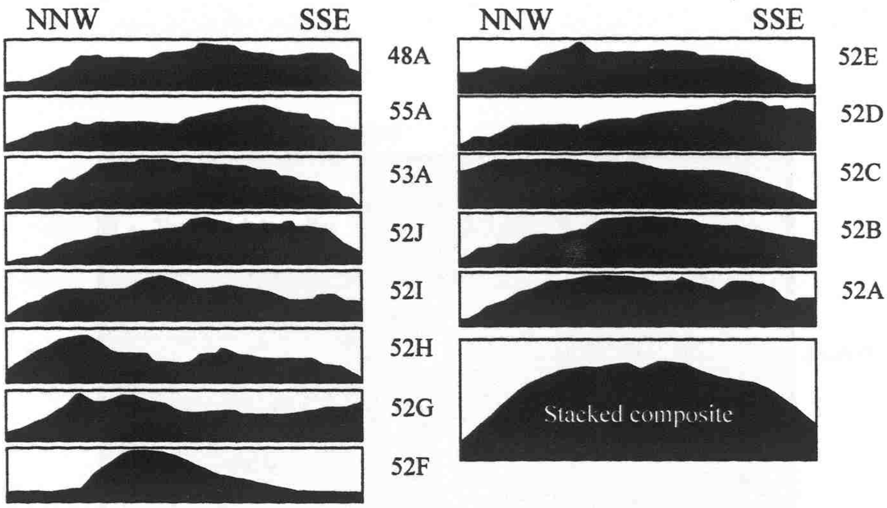


Fig. 4.8: Digitised profiles of submerged elongate topographic highs imaged beneath Strangford Lough. These profiles were generated by digitising TWTT Boomer sections, then normalising measurements of length and height.

Three combined Chirp / 100 kHz side scan profiles were obtained in the vicinity of features 52I, 52J and 53A (fig. 4.9). Side scan sonographs provide indication of slope directions in this area, which are consistent with the presence of discrete, elongate topographic highs orientated approximately parallel to the direction of ice flow. Measurements from Chirp profiles orthogonal to the Boomer data suggest apparent widths of 250m and 242m for features 52J and 53A respectively, providing aspect ratios of 2.5:1 and 1.7:1.

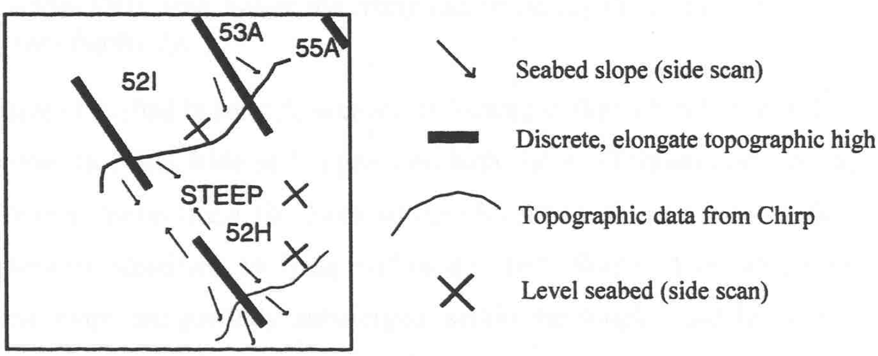


Fig. 4.9: Sketch of seabed and subsurface information compiled from Boomer, Chirp and side scan sonar records of the northernmost end of the Southern basin of Strangford Lough.

These features are located in a region of the lough whose shores and shallow-water areas exhibit numerous drumlins (fig. 4.10), identified and measured by Vernon (1971).

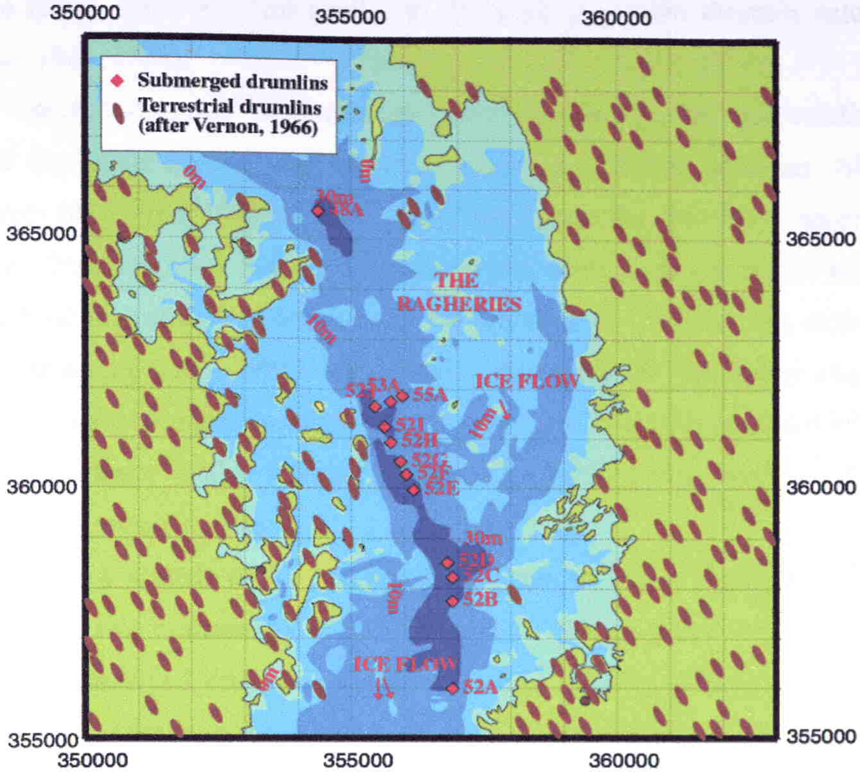


Fig. 4.10: Location of drumlins, measured by Vernon (1966, 1971) and submerged topographic maxima discovered by seismic survey, superimposed upon the bathymetry of southern Strangford Lough. The submerged features all lie in deep water (below c. -30m OD), well below the likely maximum depth of late- and post-glacial erosion (see chapter 5).

The features identified in seismic section are located within a band of drumlins which is approximately 10km wide and appears on both shores of Strangford Lough, in a ENE / WSW orientation (fig.4.10). None of the observed features lies more than 1500m from drumlins identified as lying within this belt. Some of the drumlins identified in these maps are partially submerged within the lough[1], and lie within 500m of the features identified in seismic section. Ice flow through this region during drumlinisation was approximately NNW-SSE (McCabe *et al*, 1999). The length of features measured from seismic lines parallel to this orientation[2] (483m) lies within 2

[1] For the purposes of discussion, those drumlins lying partially submerged within the lough are termed *semi-submerged*, whilst those without marine contact are *terrestrial*.

[2] Measurements of length taken from aerial photographs are likely to be lower than those derived from seismic data, as the former measures only the length of drumlin visible as surface expression through late-glacial sediments and recent regolith. These values may thus be closer than is suggested in the text.

standard deviations (σ = 81m) of mean drumlin length (355m) reported from the surrounding shore (Vernon, 1971). Where measured, aspect ratios for the submerged features (2.5:1 and 1.7:1) are similar to the mean measured drumlin value of 2.1 (Vernon, 1966, 1971).

Observations and measurements from drumlins on the surrounding shore indicate that these features may represent submerged, buried drumlins. Alternative arguments have been advanced, including the suggestion that they represent push moraines. Push moraines form distinct, linear side scan sonar anomalies with visible surface boulder scatter, lie transverse to the direction of ice flow, and lack coherent internal structure (Dix, 1996). The features observed in Strangford Lough form discrete topographic maxima, which are elongate parallel to the direction of ice-flow and contain clearly visible internal structures, which form the basis for discussion during the following section.

The low altitude of the submerged features has given cause for questioning their identification as drumlins. The bases of these features lie at c. -40m OD to -60m OD. Semi-submerged drumlins in eastern Strangford Lough extend to -15m OD, whilst terrestrial drumlins recorded by Vernon (1971) occur in roughly equal numbers within c.30m (100 foot) survey intervals between 0 and 120m OD, and in lesser numbers up to 180m OD. Sea level at the time of drumlinisation is thought to have lain between +12 and +25m OD (McCabe *et al*, 1984), yet in Strangford Lough, morphologies established as drumlins lie semi-submerged. It would appear therefore, that altitude and sea level do not provide logical arguments against identifying these features as drumlins.

Justification for identifying these features as drumlins is initially provided by their apparent dimensions and location relative to the previously described terrestrial drumlin swarms. It is to be expected that, whilst the profiles are approximately parallel to the drumlin long axes, their offset from this axis should vary. This is supported by examination of peripheral data, which suggests that some apparently short drumlins (e.g. 52F: 200m long) have been imaged at greater axial offsets.

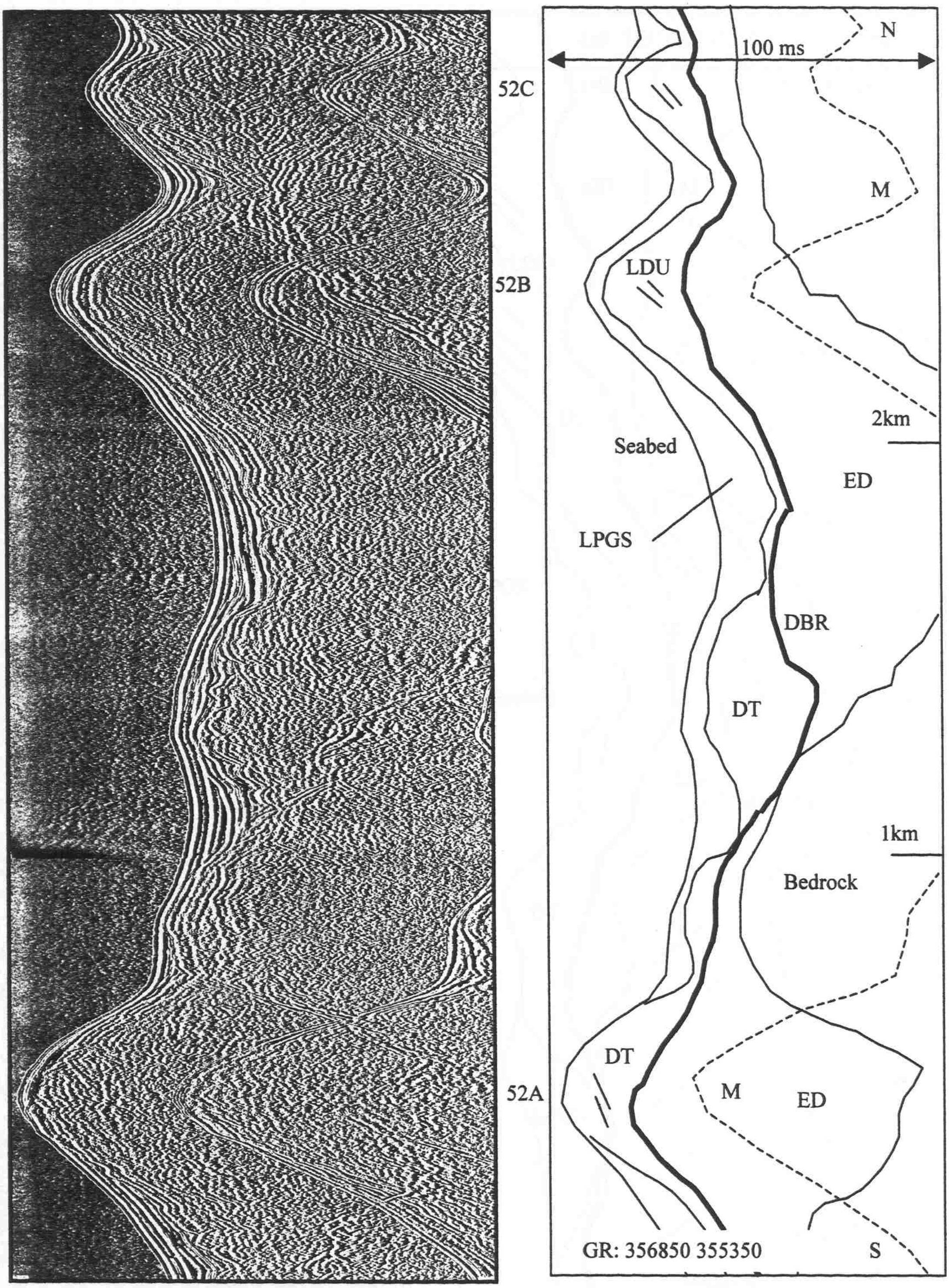
4.10: Seismic Characteristics of the Submerged Drumlins

The thirteen drumlins surveyed in Strangford Lough possess similar variations in seismic reflection characteristics along a line which is approximately parallel to the inferred mean direction of ice flow over the area. Externally, the drumlins exhibit a stoss (NNW) face, which is slightly steeper than the lee (SSE) end (fig. 4.8). This shape, coupled with the low position of the drumlins in the landscape, correlates with the "classical drumlins" described from the Omagh Basin by Knight (1997). Several drumlins also exhibit wave-like phenomena on their lee faces.

All of the imaged drumlins exhibit a clear basal reflector, which on time sections tends to be upwardly convex beneath the general drumlin high. Five of the thirteen directly overlie bedrock, whilst the remainder are underlain by a reflective surface which may represent an older glacial surface[3]. The continuous seismic reflector located beneath the drumlinised deposits is termed the Drumlin Basal Reflector (DBR); there is no seismic evidence for competent drumlin cores located above this surface. In figure 4.11, significant surfaces within seismic section 502 have been digitised. This representation clearly displays an apparent positive correlation between drumlin location and topographic highs upon the DBR.

Fig. 4.11 (following 2 pages): Boomer seismic profile and digitised interpretation of line 502 in two sections. An expansion of this data is included in Appendix II. Pseudo-3D information from the area of drumlins 52H, I & J, indicate that these structures are approximately elliptical in plan and possess aspect ratios close to those projected for this area by Vernon (1971). All contain similar internal reflection characteristics, which are examined in further detail within this chapter. DT: Drumlinised deposits, ED: Earlier deposits, LDU: Leewards-dipping unit, M: Seismic multiple, LPGS: Late- & post-glacial sedimentation.

[3] This surface may represent the upper bounding surface of the Lower Till, a lower glacial unit described by Hill (1968). See discussion.


52C
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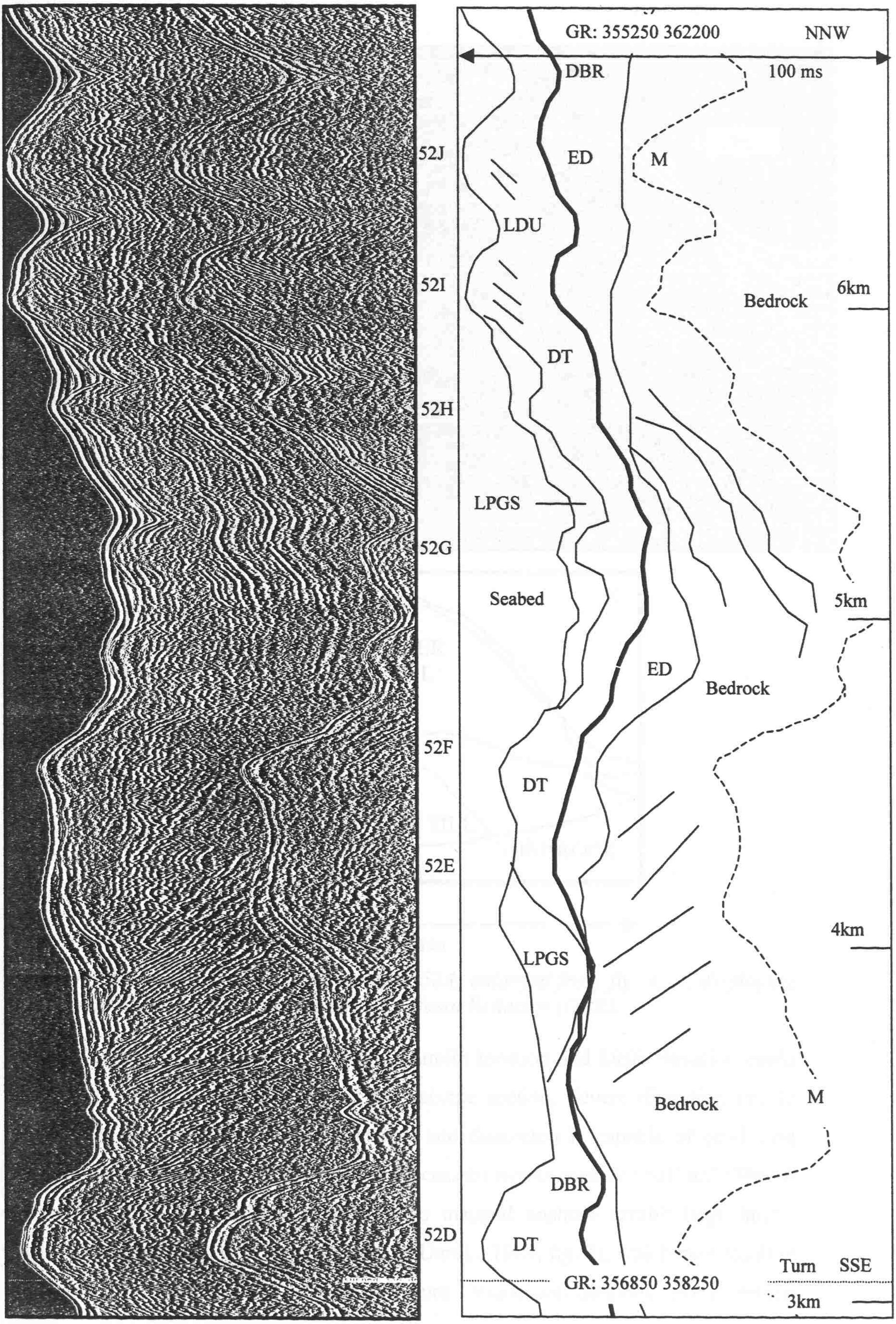
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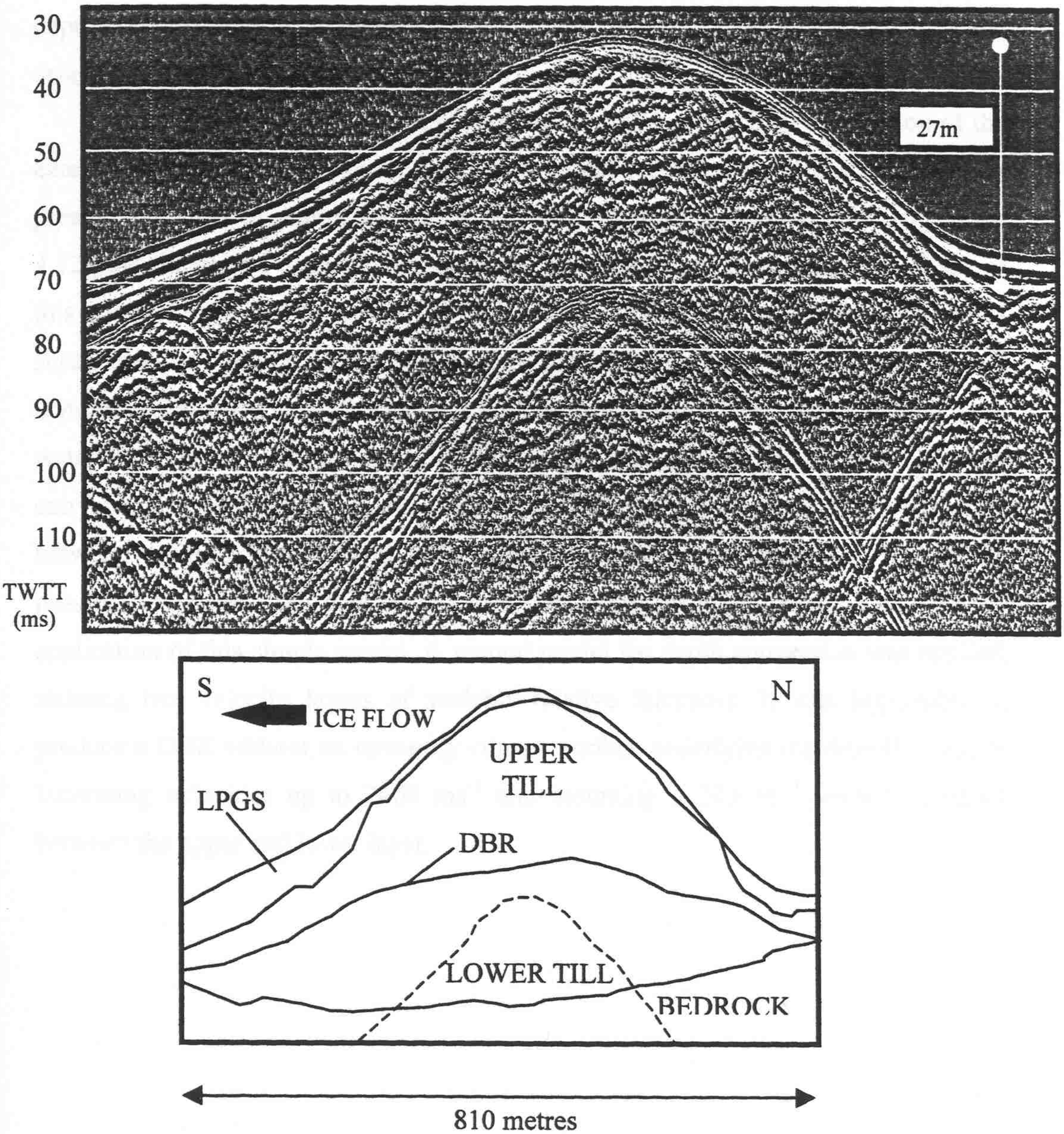


Fig. 4.12: Seismic section through drumlin 52A, enlarged from fig. 4.11, displaying the general drumlin shape and the Drumlin Basal Reflector (DBR).

The apparent correlation between drumlin location and DBR elevation could result from velocity distortion within the seismic section. Severe distortion due to strong velocity contrasts between seawater and diamicton is capable of producing false basement highs beneath drumlins, a process known as seismic "pull-up" (Sheriff & Geldart, 1982). Drumlinised till deposits mapped onshore exhibit large lateral variability in sediment type (e.g. McCabe & Dardis, 1989, fig. 2), which may result in a highly complex seismic velocity structure. Velocities obtained from seismic refraction on nearby beaches and pladdies proved insufficiently accurate for use in depth conversion; this necessitated a less direct approach to an investigation of the origin of this apparent correlation.

A simple model of drumlin shape was formed in TWTT by digitisation of the external form of the most prominent drumlin imaged (52A). This drumlin possesses a greater thickness of diamicton above the DBR, than its contemporaries (fig. 4.11, 4.12), yet the glacial deposits almost pinch out at the drumlin margins. The shape of this drumlin and the thickness of diamicton within, suggest that it is the most susceptible to pull-up. This shape was then depth converted for a range of compressional wave velocities suitable for till (Jensen *et al*, 1994) and assuming a sea water velocity of 1481 ms^{-1} (Fig. 4.13). If the DBR could be flattened by depth conversion at reasonable seismic velocities, then the apparent positive correlation between drumlin location and DBR topography would be unreliable. It was not possible to recreate the consistent correlation observed in the seismic data set by application of this simple model. A second model for depth conversion was applied, utilising two velocity layers of variable relative thickness. It was impossible to produce a DBR without an upwardly convex surface underlying the drumlin, despite increasing velocities up to 2400 ms^{-1} and assuming a 300 ms^{-1} velocity contrast between the upper and lower layer.

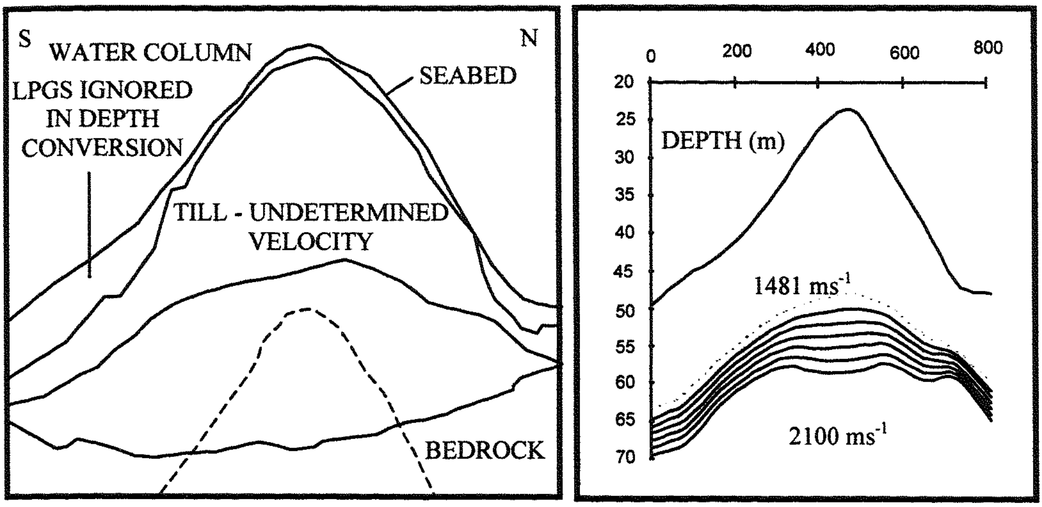


Fig. 4.13: Demonstration of single-layer depth conversion for drumlin 52A, which assumes a homogenous internal velocity structure. Depth conversion was conducted in 100ms^{-1} intervals, from 1600 to 2100 ms^{-1} (above right). The positive correlation is clearly visible at all conversion velocities.

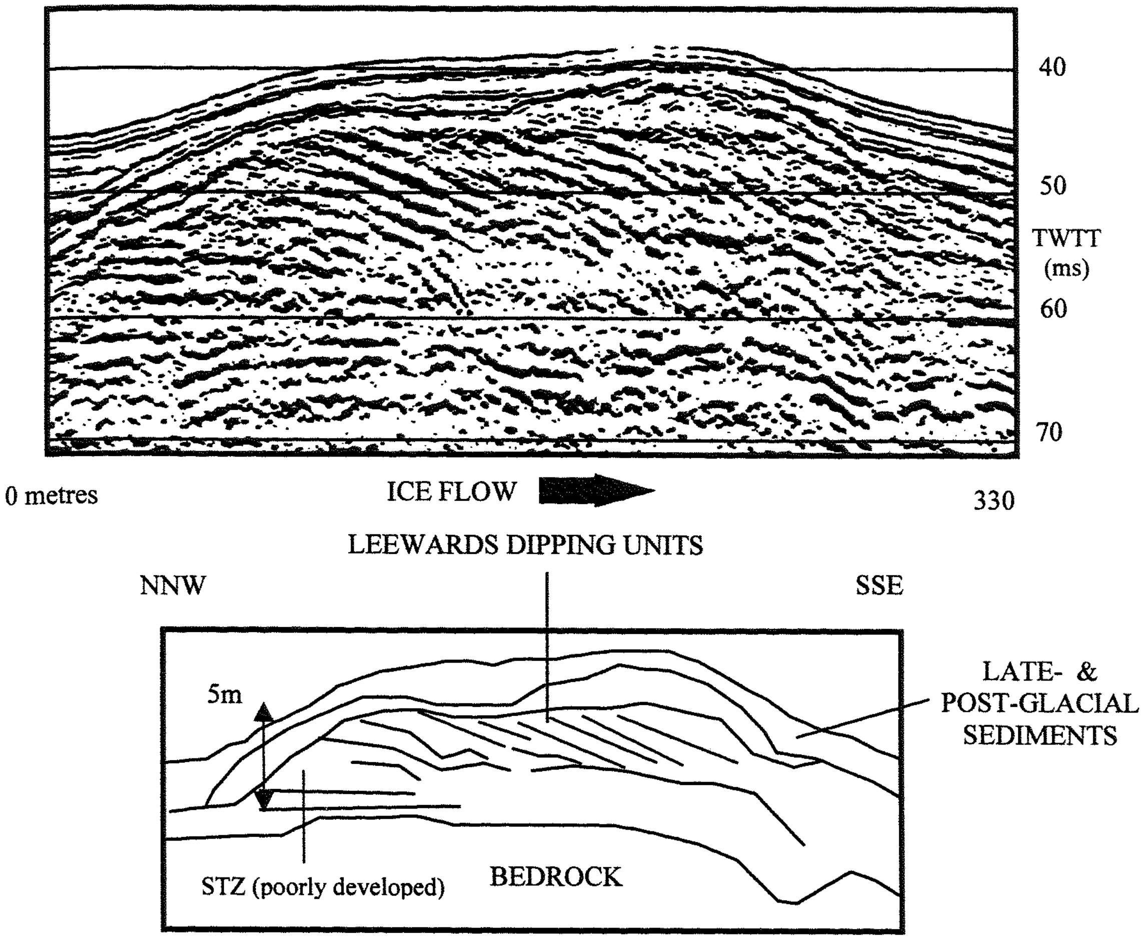


Fig. 4.14: Processed section through drumlin 52I, southern Strangford Lough. STZ: Seismically transparent zone.

The seismic structure of drumlin 52I (fig. 4.14) consists of a series of strong reflectors, which may be up to 50m in length, and lie above the basal bedrock surface. These reflectors dip towards the lee end of the drumlin, steepening distally from sub-horizontal layers at the base of the stoss end, to dips of 7-9° at the lee end. The character of these reflectors also changes distally, from linear reflections to more sinusoidal forms. Subglacial delta deposits also contain units dipping in the down-flow direction, but the angle of dip is typically 0.5-4° and proportional to delta extent, such that small structures such as those in Strangford Lough would contain only gently dipping foresets (Vanneste & Larter, 1995). Furthermore, deltaic deposits are generally not planar in plan, and thus would not produce consistent apparent dip angles in this manner. The correlation between drumlin location and DBR topography is a further argument against these dipping reflectors representing selectively preserved sections of a subglacial delta.

Drumlin 52I (fig. 4.14) consists of a bedrock base, a core containing stratified material lying leewards of a seismically transparent zone, and a mantle of seismically unstratified material, beneath a drape of late- and post-glacial sediments. Contemporary drumlin sections (e.g. figs. 4.11, 4.12 & 4.15) all contain the leewards dipping units (LDU) observed in drumlin 52I. Most (fig. 4.15) also exhibit a *seismically transparent zone* (STZ) which extends distally from the stoss end for up to a third of the total drumlin length. In Drumlin 52D (fig. 4.15) the presence of sharply reflective dipping bedrock at 40 ms indicates that non-reflection from the transparent zone is not due to acoustic blanking by a highly reflective overlying horizon.

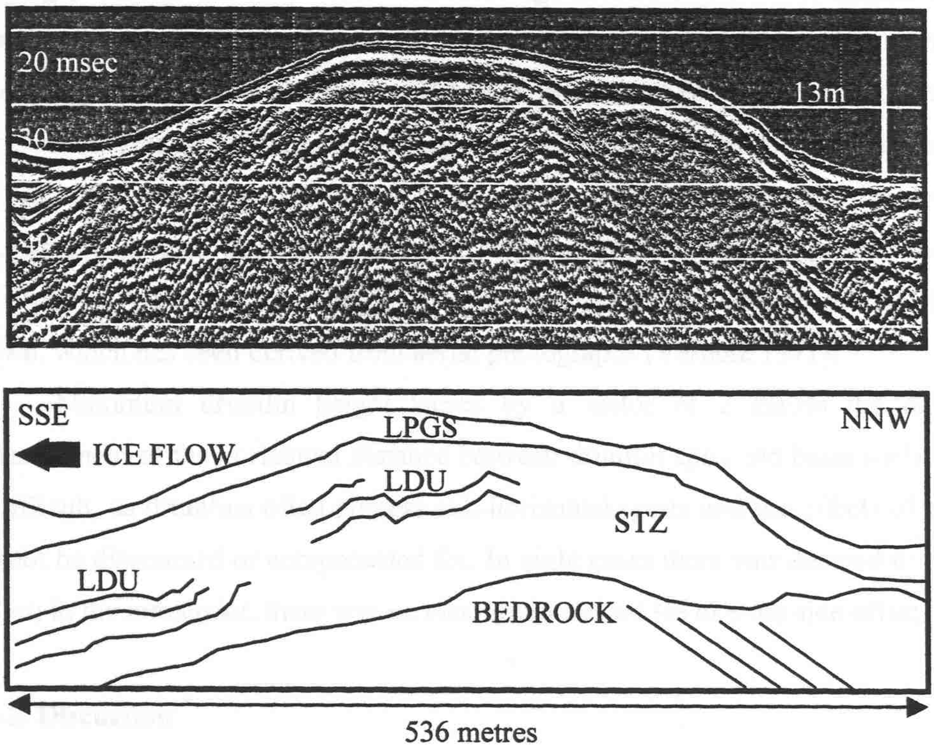


Fig. 4.15: Boomer seismic section and interpretation through drumlin 52D, located in the southern basin of Strangford Lough. In this drumlin, bedrock forms the DBR, above which the Seismically Transparent Zone and Leewards Dipping Units are clearly visible.

Comparison of the above data with recent published examples of high-resolution marine seismic surveys over drumlins suggests that this data set represents a step forward in data quality and continuity. Previous surveys have been successful in identifying active drumlin erosion (Oldale *et al*, 1994) and the diamict – bedrock relationship (Lewis *et al*, 1997). Results presented within this chapter are the first to yield clear, detailed images of the internal structure of submerged drumlins and the relationship of drumlin structure to the underlying substrate. The need to compare structural data from large numbers of drumlins has been identified elsewhere (Patterson & Hooke 1995, Hart 1997), but this study demonstrates how detailed, quantitative data might be gathered rapidly, for intra- and inter-swarm structural comparison.

Measurements of diamicton thickness, drumlin length, drumlin apex position and the position of any underlying bedrock high were made for each of the thirteen submerged drumlins (Appendix III). Statistics were compiled for all drumlins, irrespective of seismic line orientation, although the significance of any trends is hard to gauge, due to the difficulties in establishing true orientations and lengths for the sample set. Apparent length varied between 190m (52F) and 811m (52E). Drumlin mean length over the till substrate (550m) exceeded that of bedrock-based drumlins by c. 110m. This agrees with the findings of Patterson & Hooke (1995) which indicate that drumlins are better developed over areas of thick underlying drift. Drumlin lengths are greater than the published mean adjacent terrestrial values and also contradict a trend towards shorter drumlin length with decreasing altitude in Co. Down, which has been derived from aerial photographs (Vernon, 1971).

Maximum drumlin height varies by a factor of 2 across the data set. Measurement of the horizontal distance between drumlin apex and basal surface high is difficult, as drumlins often possess sub-horizontal crests and the effects of pull-up cannot be discounted or compensated for. In eight cases there was deemed to be zero offset; in the remainder, there was no clear trend toward lee or stoss side offset.

4.11: Discussion

Study of seismic images through adjacent drumlins within Strangford Lough has yielded information upon the drumlin-substrate relationship and the cross-swarm similarity of drumlin internal structure. Interpretation of these images is dependent upon published information concerning contemporary sites within the northern Irish drumlin belt. Deposits on the surrounding shore are described by Hill (1968), who identified upper and lower glacial till units as belonging to separate glacial events. Whilst this cannot be proved or disproved, seismic evidence suggests that in Strangford Lough, a lower glacial unit does underlie the later drumlinised material.

The discovery of a positive topographic relationship between drumlin location and basal reflector is supported by Hill (1968), who reports numerous examples of drumlins underlain by a low-relief bedrock core and speculates upon the presence of further, undetected core bodies. Drumlins comprising a significant thickness of upper till, overlying a core of lower till are also common. Elsewhere, Raukas & Tavast (1994) report a similar drumlin – bedrock relationship from the Fennoscandian shield discovered by gravity survey.

This positive correlation may be significant to the determination of a triggering mechanism for drumlinisation. The presence of a relatively subtle topographic high may be sufficient to trigger deposition, in the case of either fluvio-glacial or deformational drumlin formation (see section 4.4). As all of the drumlins imaged during this survey exhibit this correlation, it appears that the position of the drumlin is directly related to the underlying feature. A transient origin for drumlin triggering - such as an agglomeration of boulders or coarse material (Menzies 1977, Hart 1995) - is thus unlikely in this situation. Menzies (1989b) is incorrect in his general dismissal of the possibilities for detecting sub-drumlin trigger structures. Mobile trigger perturbations are probable in other localities, but such a theory appears inapplicable to the submerged drumlins of Strangford Lough.

Interpretation of processed digital boomer data from central Strangford Lough has established the broad internal structure of submerged drumlins in this area (fig. 4.16). The basic structure comprises an underlying topographic high, a stoss-end seismically transparent zone interpreted as representing unstratified till, a series of leewards-dipping (7-9°) diamicton units and a thin (1-3m) unstratified till carapace.

There is a wealth of published data and formational hypotheses from the main Irish drumlin belt (e.g. Vernon 1966, Dardis & McCabe 1983, 1987, Hanvey 1987, Dardis & Hanvey 1994, Meehan *et al* 1997, Knight 1997). In the absence of coring, analogies must be sought from terrestrial drumlins exhibiting similar internal structure. Such an approach cannot provide unequivocal evidence in favour of any particular structure, but does yield insight on the possible origin of the submerged drumlins.

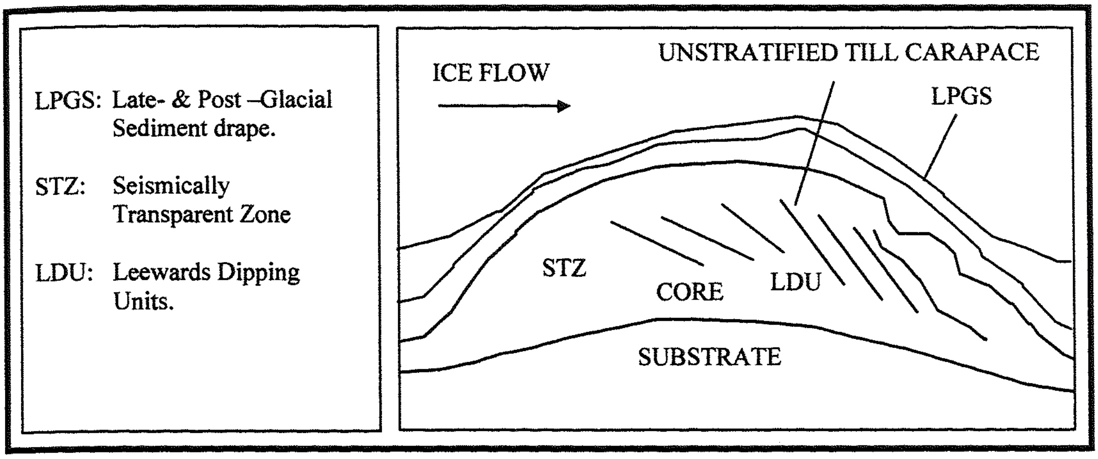


Fig. 4.16: Generalised interpretation of the internal structure of submerged drumlins from Central Strangford Lough. LDU: Leewards Dipping Units, LPGS: Late- and Post-Glacial Sediment cover, STZ: Seismically transparent Zone.

Knight (1997) observes that classically shaped drumlins of the Omagh Basin occur in low-lying regions and often contain structures related to fluvio-glacial formational process. An abundance of fluvioglacial deposits has been reported from all levels within the upper till in low-lying regions of the Lagan Valley (Hill, 1968), again implying that large quantities of meltwater were present during deposition. It is thus likely that the drumlins of Strangford Lough will contain structures related to a high level of sediment saturation.

It has been suggested (Rose pers. comm., Hart pers. comm.), that these drumlins are ice-moulded erosional remnants draped by a melt-out till carapace. As previously discussed (4.9), the presence of a consistent internal structure and topographic correlation is not supportive of this suggestion. Accordingly, a depositional or deformational origin is assumed. This broadly agrees with the opinion of Boulton (1996), who suggests that ice-marginal environments favour depositional forms, and of Knight (1997), whose study of the Omagh basin indicated a correlation between low-lying topography and depositional drumlins. Hill (1968) ascribed the majority of drumlins investigated in the Strangford Lough region to depositional processes.

Meehan *et al* (1997) describe drumlins at Kingscourt (fig. 4.4), 70km south-west of Strangford Lough, containing detached slabs of bedrock, up to 10m long and a metre thick. Such slabs might cause seismic reflection similar to that observed in the

Strangford Lough sections. Although a Triassic sandstone source is possible, it is unlikely that slabs 50m in length could be transported and stacked in such a coherent fashion. Furthermore, the slabs observed at Kingscourt dip into the direction of ice flow. McCabe *et al* (1999) identify the Kingscourt slabs as remnants of a pre-existing ridge created during ice mass flow event B and streamlined during event C. The LDU's of Strangford Lough exhibit a consistent NNW/SSE orientation; this would not be the case if these drumlins were formed during the NE-SW ice flows of stage A. A structure comprising bedrock slabs is, in summary, unlikely.

Calculation of the seismic reflection coefficient for LDU's in drumlin 52I, by a method identical to that of Bull *et al* (1998) suggests that the reflecting surfaces are highly irregular in profile. A large contrast in acoustic reflectivity is required if deep, sharp reflections are to result from the low energy Boomer source. This suggests that the LDU's are formed by horizons of dense material intercalated between less dense sediments. It is difficult to reconcile the Boulton (1996) deformation model with the occurrence of multiple dipping layers exhibiting such reflective characteristics.

Current deformational hypotheses appear incapable of producing the general internal structure described in figure 4.16. Meltwater concentration in the low-lying lough environment favours deposition in super-saturated conditions, either by large-scale fluvial flood events or by deposition of sediment slurries possessing low shear strength. There are several exposures within the Irish drumlin belt, which exhibit structural similarities to the seismic data.

Eyles & McCabe (1989) record submerged systems of *tunnel valleys* (Boulton & Hindmarsh, 1987) on the north-western margins of the Irish Sea. Strangford Lough may have provided a drainage conduit for escaping meltwater in a similar fashion to the Poyntzpass tunnel valley, 40km west of Strangford Lough (fig. 4.4). Internal structures described from drumlins within this feature, particularly Jerretspass (Dardis & McCabe, 1983), are similar to the model presented in fig. 4.16. This sand-bodied drumlin is approximately 500m in length, and is covered by a carapace of melt-out till 5-10 metres thick. (fig. 4.17).

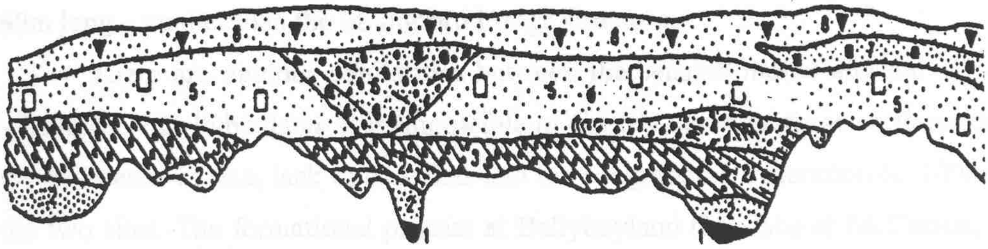


Fig. 4.17: Sedimentary facies of the Jerretspass drumlin, after Dardis & McCabe (1983). 1: Bottomset beds, 2: Toeset beds, 3: Foreset beds, 4: Topset beds, 5: Lower till facies, 6: Sediment gravity flow facies, 7: Massive diamicton facies, 8: Upper diamicton facies.

The toeset beds (unit 2) are low angle (c.5°) beds of 3-4 metres thickness, which grade up into the foreset beds (unit 3) Foreset beds are 3-10 metres thick, containing units of 0.3 to 1.2 metres; foreset bed dip decreases distally from 30° to 15°. The composition of the foreset beds is described as containing 70% pebbles and cobbles, 25% coarse sand and 5% silt and clay. There are similarities between the Jerretspass drumlin and the Strangford Lough data, despite the overall geometrical differences. The foreset beds demonstrate that leewards dipping units on a similar scale to those observed in Strangford Lough can be formed in a water-rich environment. This drumlin lacks any structure correlatable with the seismically transparent zone, whilst the angle of foreset dip is steeper than observed in seismic section. The Jerretspass drumlin is thought to have formed in several stages; streamlining is envisioned as occurring during a later stage of ice flow (Dardis & McCabe, 1983).

A drumlin bedform which closely resembles the seismic model, has been mapped in Ballyboyland Quarry near Coleraine, by S McCarron, of the University of Ulster (Fig. 4.18). Field inspection of this site by the author revealed significant correlative elements between seismic section and cliff exposure. There is a visible topographic high beneath the drumlin, consisting of rugged, truncated bedrock. At the stoss end of the drumlin is a zone of brecciated boulders set in unsorted sediment, which would produce a chaotic zone of reflectance. Behind this zone, the drumlin develops in a series of leewards-dipping bedded units 1-2m thick. Each unit is capped with scattered clasts up to 50cm across. A similar arrangement of clasts might explain the strong but irregular seismic reflections observed from the leewards dipping units of Strangford Lough. The drumlin is capped by a continuous layer of massive diamict, which is 1-2m thick, interpreted as melt-out till. The observed section is 8m high and

60m long - smaller than the Strangford Lough structures.

There are obvious similarities between the seismic model and the exposure witnessed at Ballyboyland. It is impossible to directly correlate these sections, due to the difference in size, lack of core data and the geographical separation (c. 100km) of the two sites. The formational process at Ballyboyland (McCabe & McCarron, pers. comm.) is thought to have involved multiple stages under changing subglacial conditions. An obstruction to flow was created by initial erosion of bedrock (c.f. Knight, 1997). This was followed by deposition of sheet flows down the lee slope of the obstruction, in the presence of high meltwater volumes. Finally, streamlining and melt-out deposition of the till carapace occurred. It is possible to explain all of the seismic characteristics of the Strangford Lough drumlins in terms of such a process, but without evidence this is merely a speculative acknowledgement that this analogy may suggest similar active processes operating within the lough during drumlinisation.

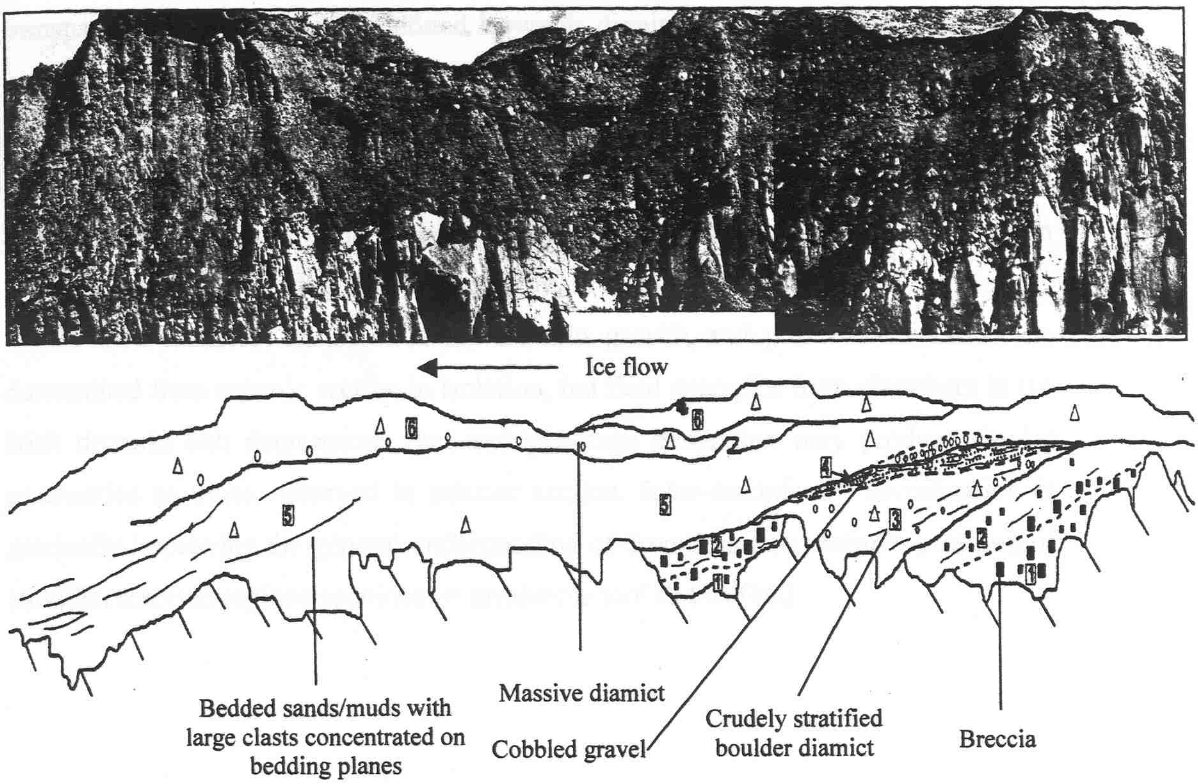


Fig. 4.18: Ballyboyland Quarry drumlin photograph and sketch, kindly provided by Steve McCarron, University of Ulster. Section length is c. 60m, height is 8m.

4.12: Conclusions

The potential of high-resolution seismic surveying as a tool for imaging the internal structure and drumlin / basal surface relationship has been demonstrated by the quality of data from the 1997 survey. Strangford Lough contains a number of well-preserved submerged and buried drumlins, which lie beneath the 30m isobath. These drumlins have been imaged in 2D on a small number of seismic lines orientated approximately parallel to the direction of formative ice flow. The survey process is rapid, involves little manpower, and has now demonstrated the true potential of the seismic technique in this area. Future work is planned for the site, including a pseudo-3D seismic acquisition and coring programme. Further mapping of drumlins around the lough shores is also necessary, to seek specific structures in terrestrial exposures.

There is a definite agreement in internal structure between drumlins across the survey area. All possess a basal reflector of either bedrock or older till, which in most cases forms a clearly visible topographic high beneath the drumlin apex. A general structure has been established from the seismic profiles. This comprises a seismically transparent frontal zone, well-defined leewards-dipping units and a thin, unstratified carapace. A positive correlation between the Drumlin Basal Reflector and drumlin location has been established. This agrees with the findings of Patterson & Hooke (1995) and Raukas & Tavast (1994), despite the dissimilarity of the drumlin type and setting. The suggestion is therefore made that irregularities in the substrate play an important role in triggering drumlin initiation, in certain environments.

The processes responsible for drumlin growth and preservation cannot be determined from seismic section in isolation, but field examples from elsewhere in the Irish drumlin belt demonstrate that multiple-stage generation may produce similar geometries to those observed in seismic section. Inter-disciplinary investigation is gradually improving the general understanding of drumlinisation; seismic profiling of suitable, selected regions provides an invaluable tool to this field.

Chapter 5: The Late Quaternary Seismic Stratigraphy of Strangford Lough

Overview

Following the onset of ice retreat c.18000 yrs BP, rapidly rising eustatic sea levels contributed to tidewater ice sheet disintegration in north-eastern Ireland, with consequent isostatic recovery. Interplay between eustatic and isostatic recovery rates resulted in fluctuations of late- and post-glacial relative sea level (RSL) in Strangford Lough and the Irish Sea. Midlandian tills within Strangford Lough were modified and subsequently buried beneath a depositional succession controlled by eustatic, isostatic, geomorphic and sediment supply parameters. In this chapter, the application of high-resolution seismic profiling to the mantle of sediment overlying the drumlinised landscape reveals the inter-relationship of the tills and late-glacial sediments, establishes a seismo-stratigraphy for the lough, and provides important information on the magnitude of the early Holocene sea level minimum. The resultant description of landscape evolution within and around the lough is archaeologically significant, as it demonstrates the large variability in shoreline location within the lough since the initial human population of Ireland during the early Mesolithic (c. 9000 yrs BP).

5.1: Introduction.

The relative sea level (RSL) curve for the late- and post-glacial Devensian (Midlandian) glaciation in north-east Ireland is poorly constrained, despite almost a century of study (Carter *et al*, 1989). Fluctuations in relative sea level during this period were driven by the interaction of eustatic and isostatic recovery following the last Midlandian glacial maximum at c. 22000 yrs BP[1]. Globally, eustatic sea level attained a lowstand of c. -125m OD[2] at 18000 BP and was subsequently rising whilst the final recession of the Irish and British ice sheets triggered contemporary regional isostatic rebound of ice-loaded crustal depressions (Jardine, 1982).

[1] All dates are given in Calendar years (Cal yrs) unless otherwise stated.
[2] All heights in this chapter are cited relative to Ordnance Datum (Belfast), which is approximately 0.4m above OD Newlyn.

Observational evidence for relict sea levels in north-eastern Ireland suggests a more complex history than that of the steadily transgressed north-west (Carter 1982, Shaw & Carter 1994). The record is highly fragmentary and lacks the volume of data available for the reconstruction of similarly complex curves in Great Britain (Shennan 1987, Lambeck 1996). The first significant published work on sea levels in the Irish Sea was that of Synge (1977), including a description of the categories of evidence acceptable for sea level reconstruction and the associated limitations in accuracy. Carter (1982) published the first detailed assessment of sea level data for the Holocene in Northern Ireland, including curves for the north-west and north-east (fig. 5.1). This curve has been broadly accepted by subsequent workers (e.g. Devoy 1983, Lambeck 1996), and has undergone subsequent modification (Carter *et al* 1987, 1989).

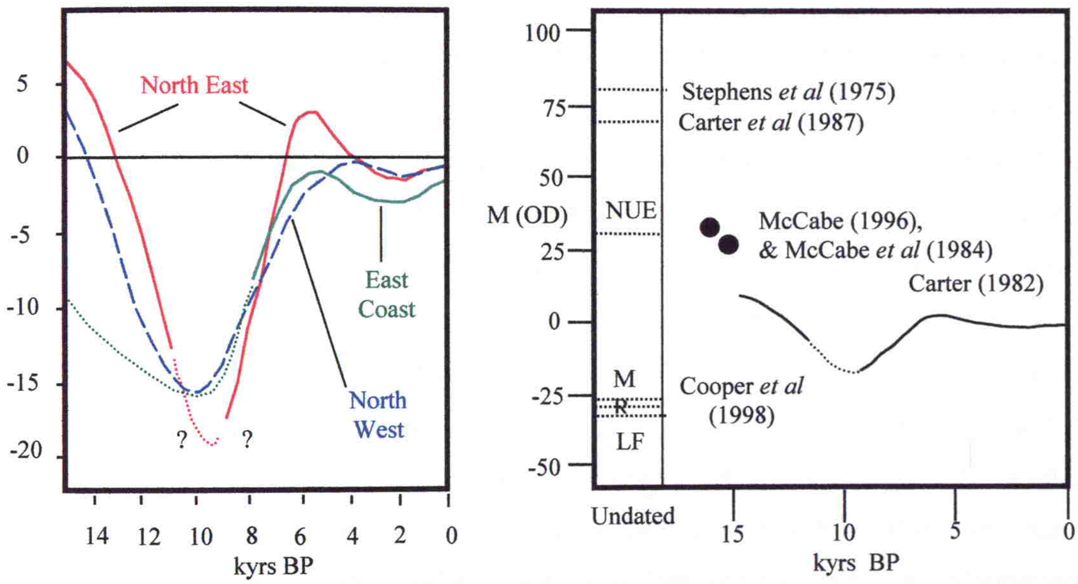


Fig. 5.1: The relative sea level curve for North East Ireland (left) has been approximately constrained by Carter (1982) and Carter et al (1987, 1989), from 15000 yrs BP. Before this (right) a series of indicator points for the north-east coast are either undated, or poorly constrained. Abbreviations: MR Maidens Rocks, LF Lough Foyle, NUE - No Unequivocal Evidence in Ireland or Britain for sea levels in excess of this height.

Published empirical RSL curves for north-east Northern Ireland (fig. 5.1) comprise a late-glacial maximum (c. 15000 yrs BP), followed by regression to a poorly defined early Holocene relative minimum (c. 9500 yrs BP). From this minimum, post-glacial RSL in the north-east climbed rapidly to a secondary maximum, located slightly above present mean sea level (MSL) (c. 5500 yrs BP) and subsequently decayed to the present level (Carter, 1982). Isostatic emergence in Ireland does not appear to be fully complete; at Malin Head, on the North coast, isostatic uplift is still occurring at a rate of c. 2.3mm yr^{-1} (Devoy, 1983). Relative sea level during and after the Midlandian was temporally and spatially variable upon several scales. On a global scale, RSL fluctuations were driven by climate change (eustacy) and less widespread - but vertically comparable - driven by crustal isostasy. On a regional scale, ice barriers controlled the transgression of isolated basins. Tidal ranges may have varied in both the long and short (lunar) term, as a function of basin size. Superimposed upon the geological record of these phenomena are the effects of ephemeral processes such as storm waves, which re-organise beach deposits, cut anomalously high platforms, and confuse the long-term shoreline record.

Strangford Lough and the adjacent Ards and Lecale Peninsulas have been historically significant in the evaluation of sea level change on the north-east coast. Records of varying glacial, marine and lacustrine conditions have been described from a large number of localities around the Lough (see below), which lay at the south-eastern edge of the main Midlandian ice sheet during late-glacial times (McCabe, 1997 & Chapter 4). The regional sea level curve (fig. 5.1) suggests that the fjord-like configuration of the modern lough bathymetry (fig. 5.2) is likely to have exerted a strong control upon the strength and duration of marine influence exerted by the Irish Sea. In particular, it is possible that during the early Holocene, base level in the Narrows (currently c. -25m OD) may have been above the post-glacial RSL minimum, thus isolating the lough from marine influence. Information on the evolution of marginal basins and depressions is important if the response of RSL to glacial loading is to be accurately modelled, although such information has previously been unavailable for the coast of north-east Ireland (Lambeck, 1996). This chapter contains the results of high-resolution seismic surveying in the central and eastern reaches of Strangford Lough. Stratigraphic control for this data is compiled from extensive publications and sediment core records[3] from the Newtownards area. The sediment distribution, contact altitudes and stratigraphic architecture are compared to that expected for the presently established sea level curves, facilitating a description of the sedimentary evolution of Strangford Lough, and improving the resolution of the RSL curve for north eastern Ireland, particularly at the early Holocene minimum.

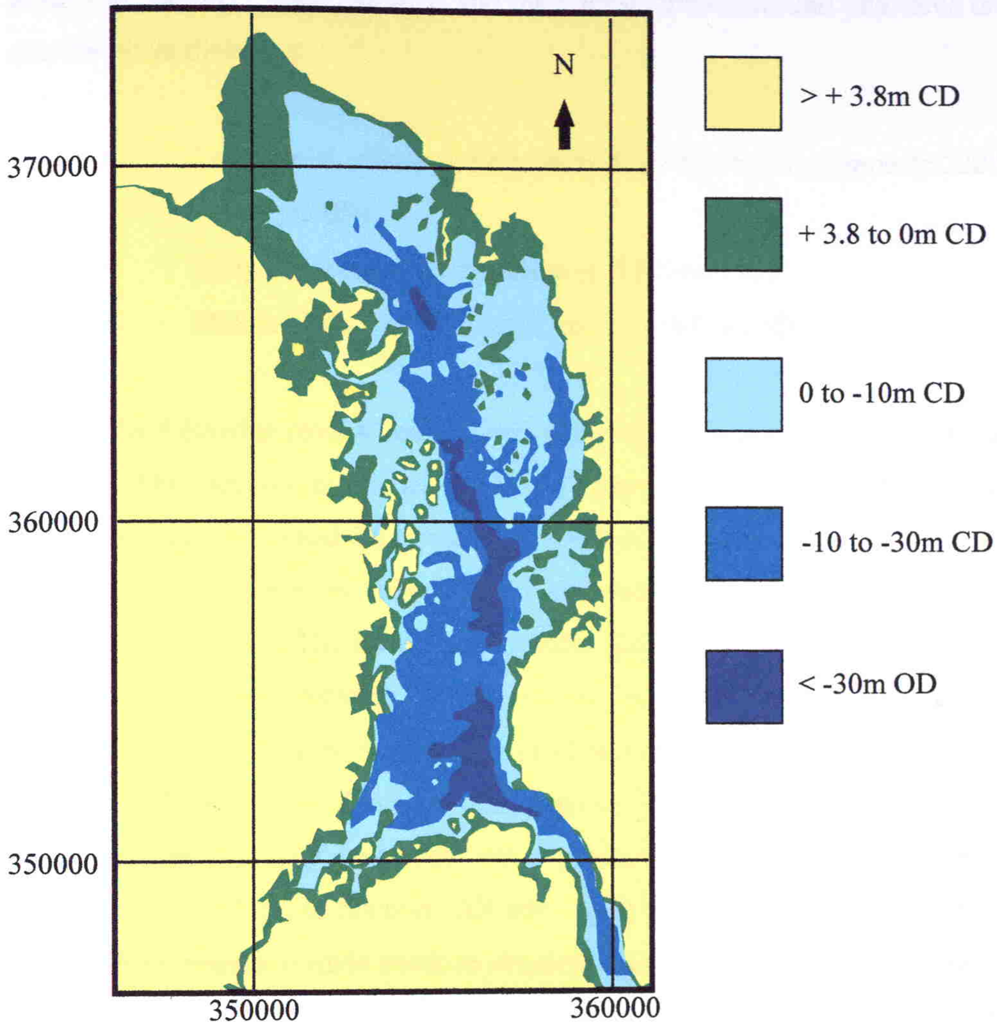


Fig. 5.2: Bathymetry of Strangford Lough. Contours have been extracted from Admiralty Chart 2156 and are relative to Chart Datum, which is approximately 1.86m below Ordnance Datum, Belfast. Grid square sides are 1km.

[3] Kindly supplied by Mr D Glynn, Newtownards Dept. of Works.

5.2: Review

Previous sea level reconstructions which were based upon evidence from around Strangford Lough, the Ards and the Lecale peninsulas, fall into three broad chronological divisions:

- Late-glacial effects during decay from the ice maximum (c.22000 - 12000 yrs BP)
- Early Holocene RSL minimum (c. 9500 yrs BP)
- Middle-Holocene RSL maximum (c. 5500 yrs BP)

The following review has adopted these approximate divisions so far as is sensible. This section concludes with a summary of the correlation between observational evidence and the results of ice-sheet rebound modelling - an attempt to predict the RSL curve by mathematical simulation of the crustal and oceanic response to glaciation. The review concentrates upon the late-glacial transgression / regression rather than debating the presence of high mid-Holocene RSL, although this latter topic has formed the main focus of previous work on Strangford Lough (Carter, 1982). This skewed focus is deliberate, as the debate over the mid-Holocene RSL maximum is largely concerned with deposits located in land-locked, currently supra-tidal, inter-drumlin hollows. All new evidence presented in this chapter is derived from marine seismic sections acquired from Strangford Lough, where the seismic stratigraphic signal due to a small (+1 to +2m OD) transgression is indecipherable from that of the bulk Holocene deposits.

Dating of organic deposits by ^{14}C methods produces ages relative to the ^{14}C time scale rather than true calendar years. Calibration curves up to 30000 yrs BP exist (see Bard 1998, Stuiver *et al* 1998a 1998b), and some of the published ^{14}C dates used in Irish sea level reconstruction were calibrated at source. Earlier ^{14}C curves - of a lesser accuracy than those more recently published - were used in these cases, and furthermore, it is not always clear from the published text whether the author is working in Calendar or ^{14}C years. In this report all dates have been calibrated to true (calendar) years BP; calibration correction has, in these cases, been made by reference to the calculations of Stuiver *et al* (1998a)[4]. Calibration of previously published ^{14}C dates is necessary for production of an undistorted sea level curve, and also for comparison of observational data with the model predictions of Lambeck (1996) for relative sea level on the Irish coast. All dates presented within this chapter are calibrated, unless otherwise stated and suffixed by ^{14}C*yrs.*

5.3: RSL during late-glacial times

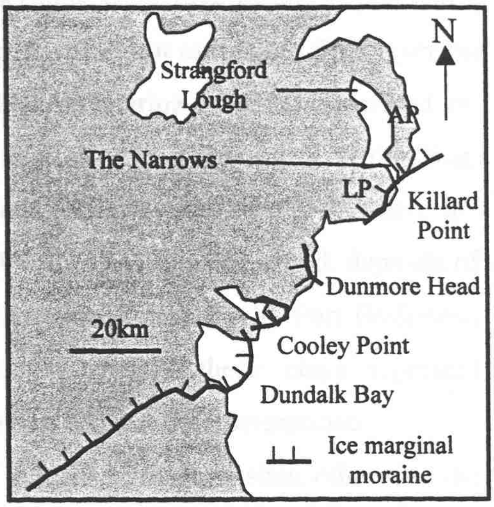
Estimates of ice thickness over north-east Ireland during the Midlandian ice maximum vary from 500m (Lambeck, 1995) to 750m (Boulton *et al*, 1985). Ice rebound modelling of the Irish and British ice sheets suggests that an ice thickness of 700-750m was likely (Lambeck, 1996). McCabe (1997) argues for a greater maximum ice thickness on the grounds that north west of Lough Neagh, glaciers breached the Sperrin Mountains (600-800 m ASL) and penetrated 50km out onto the continental shelf. The thickness and extent of the ice are key parameters in estimating both the likely rate of glacial decay and the meltwater volumes expelled at the ice margin.

The Irish Sea glacier is thought to have attained its maximum southerly extent approximately 22000 yrs BP (Eyles & McCabe, 1989), prior to a rapid eustatic sea level rise, which flooded the isostatically depressed Irish Sea basin. This marine incursion parted the Irish ice from that of mainland Britain and produced an ice-scoured topography crossed by networks of subglacial tunnel valleys (Eyles & McCabe, 1989). Ice mass flow events associated with disintegration of the main Irish ice sheet (see previous chapter) deposited banks of terminal outwash, which are observed on the Ards and Lecale peninsulas (fig. 5.3)(Hill & Prior 1968, McCabe 1997). The chronology of ice mass flow events associated with these moraines has been established by McCabe *et al* (1999). Relative sea level change associated with tidewater ice-mass destabilisation is described by McCabe *et al* (1984) and McCabe (1996, 1997) and McCabe & Clark (1998), using ^{14}C dates obtained from fossil foraminifera within red marine muds at Killard Point and Cooley Point (fig. 5.3).

[4]Calibration was effected using the software ("Calib. 4."), supplied by P.J.Reimer of Queen's University, Belfast.

This chronology commences with the deposition of muds containing the Arctic marine foraminifera *Elphidium clavatum* at Cooley Point. These red muds have been AMS ^{14}C dated to c. 19000 yrs BP. *E. clavatum* is an opportunistic marine microfaunal assemblage which has been observed to dominate the microfaunal content of recently deglaciated areas of the Arctic (Hald *et al* 1994, Haynes *et al* 1995). It has been suggested (Haynes *et al* 1995, McCabe 1996, 1997), that this microfauna is generally indicative of open water marine conditions, undergoing suspension fall-out. Examples of foraminiferal distribution elsewhere, published by Murray (1991) suggest that whilst E. Clavatum is typical of Arctic conditions, water depth cannot be fixed to any better than 0-35m. The possibility of late-glacial sea levels lower than the +25m OD suggested by McCabe *et al* (1984) and McCabe (1997) cannot, therefore, be discounted. This value is based upon evidence from Killard Point, 40km to the north-east (fig. 5.3) where terminal outwash deposits form a spread of channelised gravel interleaved with muds less than 1m in thickness, up to a height of +25m OD. A second date for *E. clavatum* at Cooley Point indicates continued open water conditions until at least 16700 yrs BP. *E. clavatum* represents the dominant marine microfauna (95%) in these sediments and has yielded dates of c.16900 yrs BP for the advancing ice front, and 16200 BP for the maximum extent of ice during this event (McCabe & Clark, 1998). The perfect preservation of this and other microfauna suggests calm depositional conditions with no subsequent reworking. A water level of at least +25m OD has been inferred during deposition (McCabe *et al*, 1984), although it is likely that RSL was falling during this period; further studies may produce evidence for later deposition of similar muds in more shallow conditions.

Fig. 5.3: Ice marginal moraines of north-east Ireland, after McCabe et al (1999). These deposits are associated with ice mass disintegration assisted by rising eustatic sea level. AP: Ards Peninsula LP: Lecale Peninsula



During the final withdrawal of ice from the southern end of Strangford Lough, high sea levels notched exposed drumlin topography at approximately +16m OD (Devoy, 1983), and deposited an overlying regional drape of red marine clay. This widespread notch was previously termed the "50' raised beach" (Stephens 1963, Morrison & Stephens 1965, Synge & Stephens 1966, Stephens & McCabe 1977, Devoy 1983). Marine incursion during late-glacial time was restricted in extent by the decaying ice sheet, thus there is no record of the absolute maximum sea level attained, nor of the true inland extent of marine inundation. The present-day topography of the Ards and Lecale peninsulas suggests that immediately post-deglaciation, sea levels of +20m OD or higher would have created an archipelago within a shallow sea (Stephens, 1970).

The raised late-glacial shorelines are draped by red muds, important exposures of which have been described at Roddans Port (Stephens 1963, Morrison & Stephens 1965), Lecale (Singh, 1970) and Rough Island, Strangford Lough (fig. 5.4)(McCabe, 1997). Devoy (1983) describes late-glacial notches on the Ards Peninsula lying between c. +14.6m and +16.8m OD as being associated with stoneless red clay, containing cold water marine fauna. McCabe & Clark (1998) identify deposits at c.0m OD on the shore of Rough Island as marine muds, with a calibrated age of 15246 ± 229 yrs BP. At Roddans Port, Morrison & Stephens (1965) describe over 4.6m of "unctuous red clay", whose origin is unclear; "*washing of samples from the tills of Co. Down has produced neither the marine fossil assemblages, nor the red clay matrix characteristic of the marine muds*" (Stephens, 1963). Singh (1970) argues against this, describing centrifuge results which show the red content of both the muds and the till separating out as a much finer layer on slow centrigugation. Further occurrences of a red marine mud are described by Stephens (1963), at Ardmillan, Glastry Cottage, Ballyquintin Point, White Bog, Killough brickworks, Dundrum Inner Bay, and Ballytrustan Townland, where the clay deposits occur at an elevation of +8m OD (fig. 5.4). Further afield, deposits of stoneless red clay have been observed at Inishowen, Lough Foyle, Port Ballintrae, Cushenden, and in Belfast Lough, although whether these clays represent synchronous deposition in a single late-glacial sea has not been determined.

There is no incontrovertible evidence to inter-relate these sites, other than the red nature of the clays; Stephens and McCabe (1977) assert that the Roddans Port and Killough Brickworks deposits appear identical, whilst acknowledging that widespread contemporaneity of the red clays cannot be established. It is possible that the deposits from some - or even all - of the sites may, therefore, be unrelated (McCabe, pers. comm., 1999). Whilst the present topography is conducive to the idea of a continuous sea across the present site of Strangford Lough, we have no information on the ice configuration during late-glacial times, and it may be that deposition at this point was highly localised, and governed by decaying ice barriers. Accepting all of the published evidence at face value suggests that sea levels during the late glacial might have attained heights of up to +40 to +50m OD in order to allow the accumulation of fine sediments in a "closed" low-energy, relatively deep water environment. Estimates of sea levels as high as +80 to +87m OD have been made, based on evidence from Roddans Port (Stephens *et al*, 1975); Carter *et al* (1987) suggest a maximum level of c. +70m OD. No unequivocal evidence for RSL above +30m OD has ever been found in Ireland or the UK.

A - Ardmillan
BP - Ballyquintin Point
BT - Ballytrustan Townland
DIB - Dundrum Inner Bay
GC - Glastry Cottage
K - Killough Brickworks and White Bog, Killough
KP - Killard Point
RI - Rough Island
RP - Roddans Port
KPM - Killard Point Moraines & contemporaneous deposits.

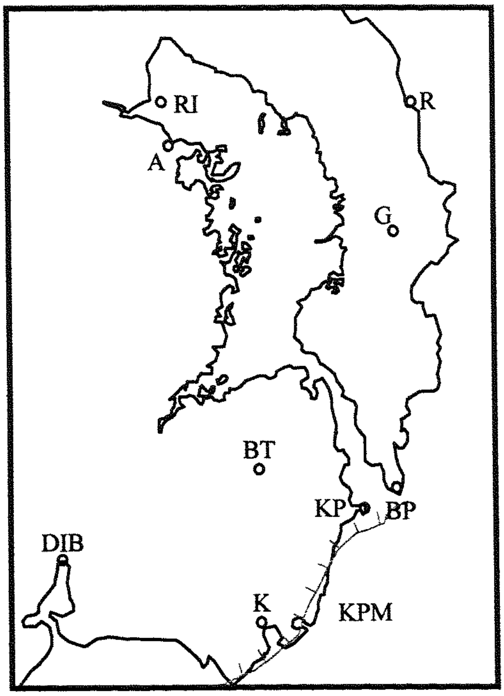


Fig. 5.4: Late-glacial sites on the Ards and Lecale Peninsulas from which "red marine clays" have been described. The location of an additional site at Cooley Point is indicated in fig. 5.3.

5.4: The Early Holocene RSL Minimum

Following the late-glacial maximum, relative sea level fell extremely rapidly as the rate of isostatic rebound exceeded that of eustatic rise (Synge & Stephens, 1966). The exact level of the RSL minimum is unconstrained, however, estimates from field evidence centre on a value of -20 to -30m OD (Carter 1982, Carter *et al* 1987). Carbon dating of terrestrial and freshwater deposits on the foreshore at Roddans Port indicate that sea level fell beneath -1.3m OD on the open coast by 13444 ± 120 yrs BP (Devoy 1983).

There is an abundance of data suggesting extremely low sea levels around the north coast of Ireland during the early Holocene. Studies of post-glacial sea level change in Ireland have often been concerned with the presence of a land bridge linking Ireland to mainland Britain. Devoy (1985) suggests the most favourable location to be the Malin Sea (c. 100 km N of Strangford Lough), where borehole data suggests that RSL in the strait between Colonsay and Jura was c. -30m OD (Jardine, 1982) during the early Holocene. Shallow borehole evidence from

Magilligan Point, Lough Foyle (100km NW of Strangford Lough) yields the transition from marine to estuarine conditions at -32m OD and back to marine conditions at -27m OD (Devoy, 1983). Submerged terraces at -90m OD and -25m OD, located around the Maidens Rocks and in the North Channel off Larne (25 km north of Newtownards) have been identified as "fresh" marine erosion terraces (Carter, 1982). Finally, Cooper *et al* (1998) identify subaerial erosion at -30m OD in Belfast Lough, 15km north of Strangford Lough.

5.5: The Mid-Holocene RSL Maximum

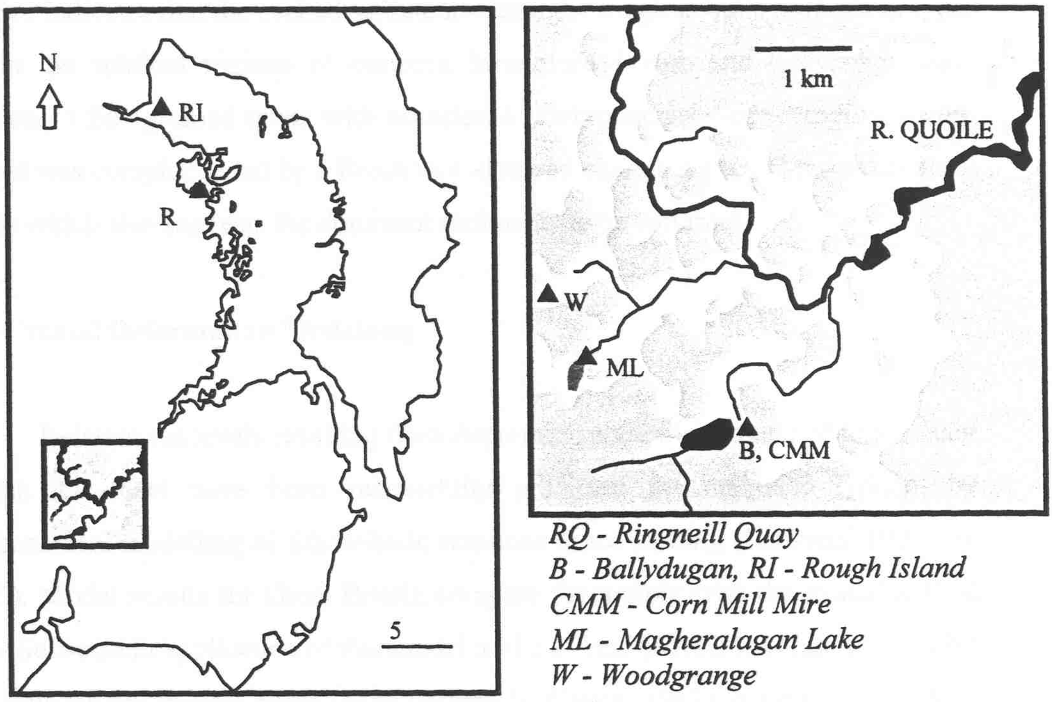
Rapid transgression of the Northern Irish coast during the middle Holocene has been recorded at a range of sites in Co. Down, the most significant of which lie on the Lecale Peninsula (fig. 5.5). Initial transgression of the east coast is recorded in boreholes beneath Belfast, where dates from marine / estuarine clays and organic peats indicate that transgression from -12 to -2m OD occurred in the period 11232 ± 100 to 8592 ± 50 yrs BP (Carter, 1982).

Evidence for continued transgression is derived from a number of inter-drumlin hollows on the Lecale Peninsula, on Rough Island and at Ringneill Quay (fig. 5.5), where the sedimentary / pollen record reflects marine inundation followed by regression during the late Holocene. At Ringneill Quay (Morrison 1961, Morrison & Stephens 1965) glacial sands are truncated and overlain by an organic marine deposit, two ^{14}C samples of which have been dated to 7656 ±150 yrs BP and 7363 ±150 yrs BP (Carter, 1982). The sharp contact between these clays and the overlying beach gravels is inferred to reflect a rapid rate of transgression.

The timing of the mid-Holocene transgressive onset in Strangford Lough has been reasonably constrained by a study of four inter-drumlin hollows (Corn Mill Mire, Ballydugan, Woodgrange and Magheralagan) on the Lecale Peninsula (Singh & Smith 1966, 1973, Stephens & McCabe 1977). Examination of inter-drumlin deposits on the Dundrum Bay (south) side of the peninsula indicates that marine incursion could only occur from the north (Strangford Lough) side, via the Quoile River (Singh & Smith, 1973). No marine deposits are found at Corn Mill Mire (lake threshold +3.1m OD, possibly artificially raised), Ballydugan (+5.4m OD) or

Magheralagan (+5m OD, artificially raised). Marine sediments ^{14}C dated to 6474 ± 300 yrs BP are present at +0.8m OD, in the basin at Woodgrange. This sample overlies freshwater organic deposits dated to 8126 ± 345 BP (+3.2m OD), 7837 ± 175 BP (+3.0m OD) and 8248 ± 400 (+0.5m OD), implying marine transgression after 7837 BP and before 6474 BP. The basin threshold height is +1m OD. From the nature of the deposits and their inter-drumlin location, Singh & Smith (1966, 1973) infer a maximum marine influence at +3.6m above present MSL (c. 1.8m OD), associated with a maximum mean sea level c. 1.2m above the present.

Dating the timing of regression to modern sea levels is problematic, as the majority of available evidence lies within zones which have undergone considerable reworking by subsequent shoreline / storm processes. Singh & Smith (1966) considered marine conditions to have persisted at Woodgrange until at least 3265 ± 150 yrs BP, on the evidence of an overlying terrestrial peat. Evidence for regression observed at Woodgrange must be considered in light of the enclosed nature of the basin, which would have been vulnerable to storm surges, following cessation of permanent marine inundation (Singh & Smith, 1973). More detailed investigation of the Woodgrange deposits has failed to provide a clear date for the final reversion to freshwater conditions, but it must post-date a widespread marine sand deposited c. 5200 BP (Carter, 1982).



RQ - Ringneill Quay
B - Ballydugan, RI - Rough Island
CMM - Corn Mill Mire
ML - Magheralagan Lake
W - Woodgrange

Fig. 5.5: Location of sites associated with the Mid-Holocene transgression of Strangford Lough. Shading corresponds to elevations over +10m OD.

5.6: Recent Deposits

There is little published literature on the recent sediments of Strangford Lough. Ryan & Cooper (1998) describe the sedimentology and evolution of the intertidal flats in Strangford Lough, centred on sites at Newtownards, Greyabbey and Ardmillan. At Newtownards, wave fetch is at its maximum and the glacial landscape has been truncated and buried by sediment deposition. The sedimentary environment of this area exhibits net deposition; sands eroded from the glacial landscape are building up extensive tidal flats. In Greyabbey Bay, wave fetch is more limited, and the drumlins are still undergoing erosion. The intertidal zone here consists of a wave cut platform in the glacial till, overlain by a thin veneer of sands reworked from the till. Ardmillan, on the west coast of the lough, is a very sheltered environment with short wave fetch; the drumlin landscape here is largely preserved, and ongoing deposition of mud-dominated tidal flats is occurring. Tidal currents are the major control on sedimentation in this area.

Deposition in the intertidal zone is not a reliable indicator of the sediment regime further offshore. A sub-littoral sampling survey by the N.I Environment

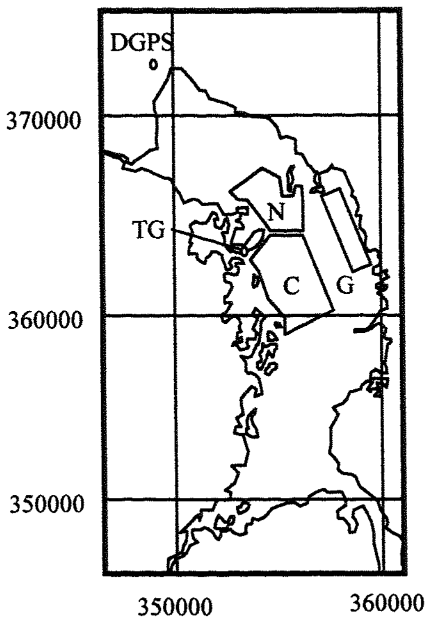
Service indicates that the seabed sediment within the lough is quite variable in type, but in the subtidal regions of northern Strangford Lough and Greyabbey Bay, consists of fine-grained muds with occasional sandy patches. Spot-sampling of the seabed was complemented by a RoxAnn and towed camera survey (Magorrian *et al*, 1995) which also suggests the dominant sediments to be soft mud.

5.7: Crustal Deformation Modelling

Relative sea levels resulting from depression and rebound related to the main British ice sheet have been successfully predicted for mainland Britain, by mathematical modelling of lithospheric response to ice loading (Lambeck 1993a, b, 1995). Model results for Great Britain compare favourably with the available field data. Subsequent application of this model to the effects of Irish ice (Lambeck 1996) can produce the general curve shape defined by Carter (1982), but on a longer time scale, such that events described by McCabe (1996, 1997) & McCabe & Clark (1998) would occur far earlier than is currently accepted. It is difficult to appraise the accuracy of the model output, however, due to ambiguities in published representation of the results (Lambeck, 1996). McCabe (1996) provides AMS ^{14}C dates for marine muds within and near to Strangford Lough, lying at 0 to +5m OD. This indicates that the model presented by Lambeck (1996) approximates quite closely to field evidence from the Holocene, but becomes significantly inaccurate when predicting late-glacial sea level change. Publication of the Lambeck model results predated that of the AMS dates for around the north coast of Ireland (McCabe 1996, McCabe & Clark 1998). The analysis and rejection of Lambeck's model results by McCabe (1997) may provide positive feedback for a subsequent and more precise model of relative sea level change around the Irish coast.

5.8: Seismic Survey Data Acquisition and Processing

A high-resolution seismic survey of central and eastern Strangford Lough was executed over an eight day period during May-June 1997 (figs. 5.6 & 5.7); details of this survey were presented in section 3.3. This chapter is concerned with interpretation of some 100km of Chirp sub-bottom profiler data acquired during this period. (fig. 5.7).



Survey Areas
NC - North Central
C - Central
GB - Greyabbey Bay

Fixed Stations
TG - Andera fixed water level recorder (Tide Gauge)
DGPS - Differential GPS correction station, on Scrabo Tower.

Fig. 5.6: Location of Chirp survey areas within Strangford Lough. See Chapter 3 for further information.

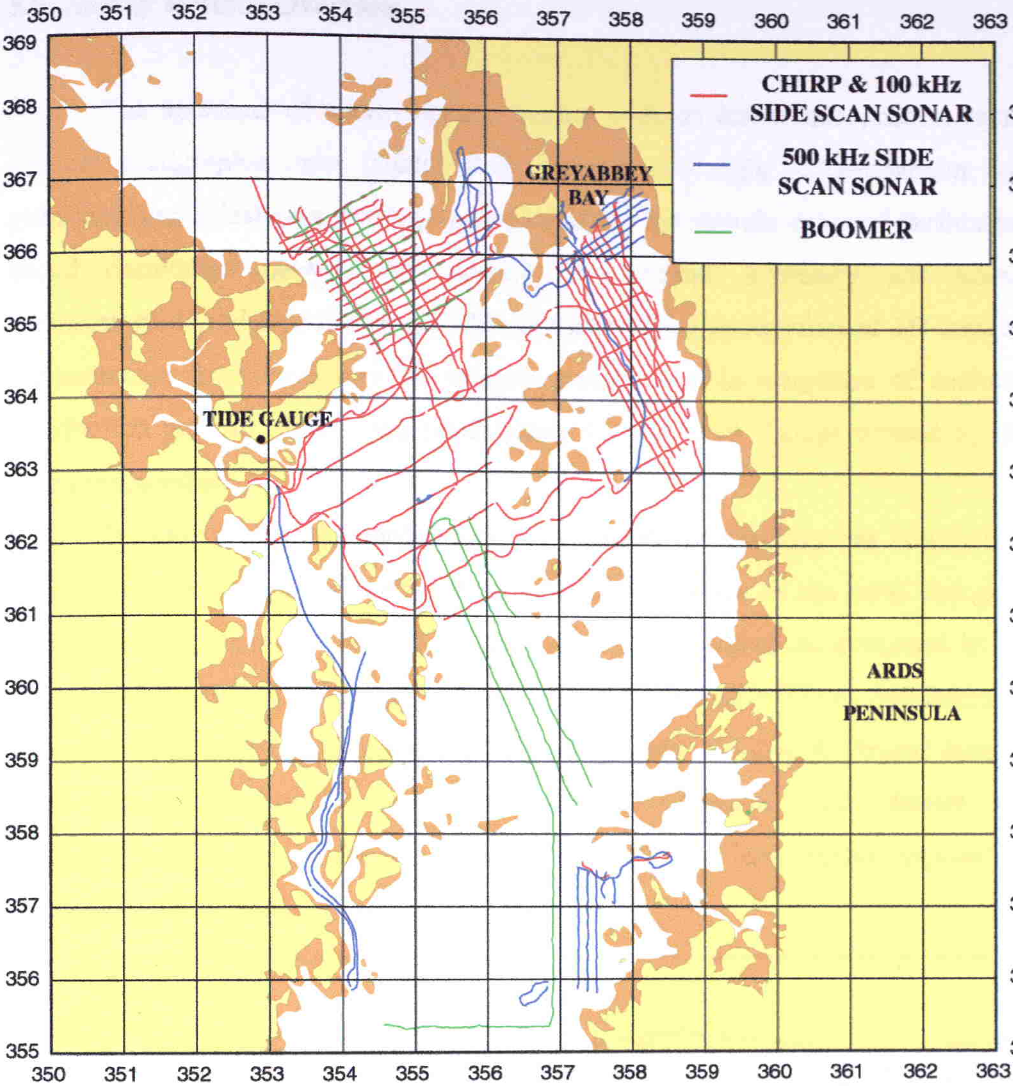


Fig. 5.7: Survey coverage within central & northern Strangford Lough. 100km of combined Chirp sub-bottom profiles and 100 kHz side scan sonar data and 27km of boomer profiles were acquired during an eight day period in May-June 1997.

All Chirp seismic data acquired was processed through an "optimum" set of processing algorithms, as described in Appendix 1. The vertical resolution of correlated, processed data is estimated at 0.35m (Appendix I). Lateral resolution varies from c.2.2m to 4.8m, with respect to depth and compressional wave velocity. Following processing, important, laterally extensive seismic horizons were digitised, corrected for tidal offset, and contoured in GMT[5]. Navigation data was added after digitising, due to hardware incompatibilities at the hardware stage.

[5] GMT: Generic Mapping Tool. A generic, UNIX environment data processing and presentation tool. See Wessel & Smith (1990) for details.

5.9: Survey Results: Overview

The appraisal of survey results begins with an initial introduction to the seismic stratigraphic units identified in Strangford Lough. A comparison with published geological data provides ground truthing for seismic data and facilitates a broad correlation between the seismic stratigraphic geometry and known sedimentary deposits of the lough. This is followed by description of 3D surfaces reconstructed from cross-tied 2D seismic profiles, for investigation of sediment distribution pattern. Finally, the implications for sea level change created by this data are discussed.

Development of standard seismic stratigraphic terminology has largely been concerned with large-scale sediment geometries and cycles of sea level change of longer duration than the "5th order" late Quaternary fluctuations discussed in this chapter. The successful study of 5th order cycles (Vail *et al* 1977) by application of seismic stratigraphic techniques to very high-resolution (Boomer & Pinger) data has been demonstrated by Chiocci (1994). Chirp data presented in this chapter is of greater resolution and smaller scale than previous studies, but a similar approach to the problem is adopted (fig. 5.8).

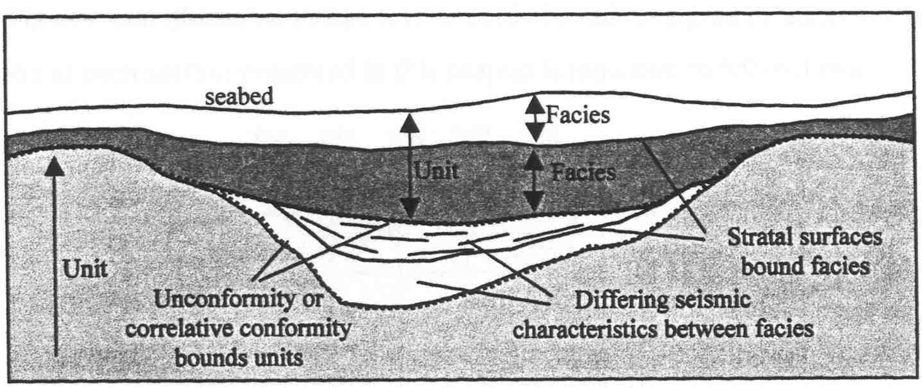


Fig. 5.8: Terminology employed during seismo-stratigraphic description of deposits in Strangford Lough.

Individual reflectors inferred to arise from changes in density and seismic velocity are termed *stratal surfaces* in accordance with standard seismic stratigraphic terminology (Vail *et al* 1977, Brown & Fisher 1985). Reflectors bounding areas of similar seismic character (reflector geometry, internal reflection) are grouped into *seismic facies*. Facies are grouped into *units*, bounded by unconformities or their correlative conformable surfaces. The term *unit* may correspond to the more standard *sequence*, although the overall geometries encountered here differ from the standard *systems tract* representations (Emery & Myers, 1998), possibly due to the unusual physical setting. For convenience, the underlying glacial deposits are also classified as a seismic *unit*; demonstrating that this designation does not infer any specific environmental relationship between its subjects.

5.10: Seismic Stratigraphy of Strangford Lough

Chirp and boomer sections from Strangford Lough exhibit a spatially variant stratigraphy, reflecting localised changes in the active sedimentary process. Data from the Greyabbey Bay (east central) region contains fewer and more easily distinguishable unconformable surfaces, whilst the architecture of the central and north-central areas is more complicated. Despite evidence for differing environments within these areas, it is possible to correlate stratal surfaces and unconformities between them. Observations upon the processed chirp data are described below, and illustrated in figs 5.10 to 5.15. To reduce figure ornamentation, the location of each section presented in this chapter is indicated in 5.9 (below).

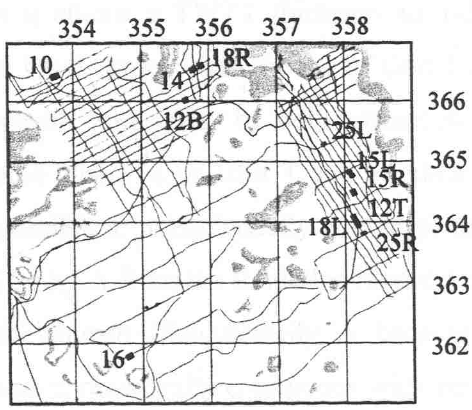


Fig. 5.9: Location of sections from which the previous and following figures, 5.10-5.15 have been extracted. Figure numbers are referred to by their suffixes (e.g. 10 = 5.10). L,R,T,B refer to Left, Right, Top and Bottom where multiple images are presented.

General Stratigraphic Description

Data presented in the previous chapter suggests that the lowest geological unit detected by seismic means is Ordovician / Silurian bedrock, observed on Boomer data from the south-central basin of Strangford Lough. In more northerly areas, gently-dipping strata thought to represent Triassic sandstone, are erosionally truncated and overlain by glacial deposits, relating to the Midlandian and possibly earlier glacial stages. The internal structure of drumlins observed within the uppermost glacial deposit, and their inter-relationship with the underlying strata, was described in Chapter 4. It is assumed that the seismic reflection from the top of the glacial deposits represents an unconformity. This surface can be identified in all records and forms a seismic basement surface, from beneath which there is generally no detectable acoustic return when using a Chirp source. This surface is therefore termed Unconformity A. For convenience, upper till deposits representing acoustic basement are considered to belong to Unit 1.

Unit 1

In addition to glacial deposits (see previous chapter), this unit comprises a single seismic facies, which is only rarely observed in seismic section.

Facies 1: This facies is observed in two locations within the central and northern basins, where it attains a TWTT thickness of 1-5 ms. The strength of acoustic return from the basal contact with the top of Unit 1 is very low, suggesting some similarity in acoustic properties. In both instances, this facies fills deep hollows within the glacial deposits of Unit 1 and exhibits weak internal seismic stratification. It is not possible to unequivocally determine the relationship between this facies and Unconformity A from the limited evidence available. This facies has been tentatively placed beneath Unconformity A because the contact with the overlying facies 2 appears geometrically contiguous with the unconformable surface (fig. 5.10), suggesting that facies 1 was affected by Unconformity A. In Greyabbey Bay there are no clearly identifiable examples of this facies.

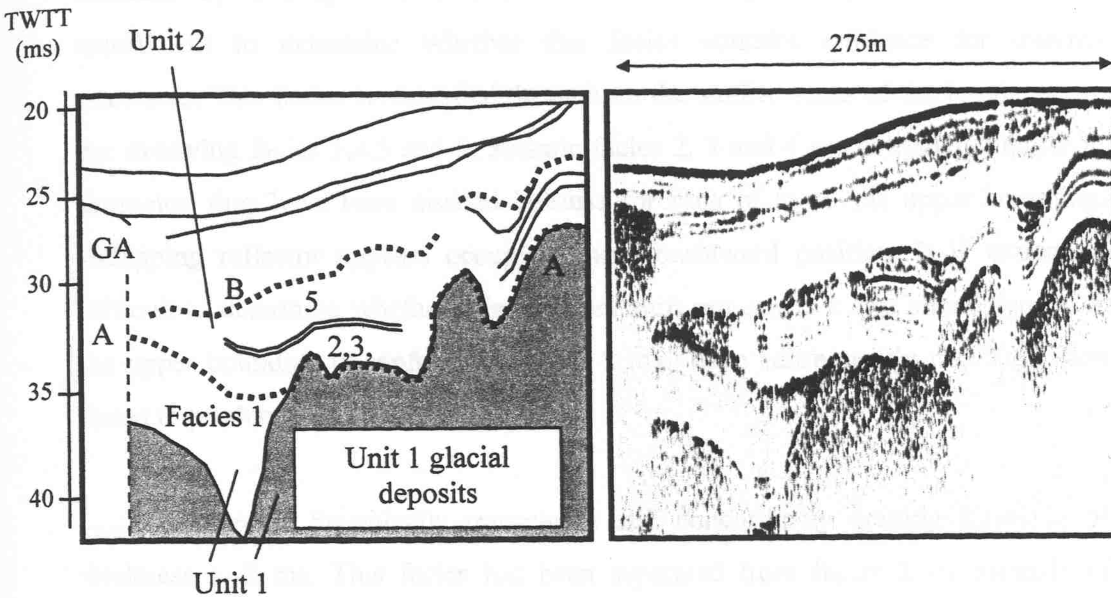


Fig. 5.10: Enhanced pre-processed seismic section from the north-westernmost survey line in the northern basin. A fully processed section is not presented, as f-k filtering suppresses the steeply-dipping upper surface of Unit 1. Seismic stratigraphic facies 1 is observed in this section, infilling an apparently incised depression of c. 5m depth. The apparent continuity between Unconformity A and the contact between facies 1 and 2 suggests that facies 1 belongs within Unit 1.

Unconformity A: This surface exhibits a hummocky topography in both the Greyabbey Bay, central and northern basin regions; returns are observed between 2 and 35 ms TWTT in Greyabbey Bay and 5 to 54 ms in the central area. In Greyabbey Bay, this surface is frequently cut by incised notches, approximately 1-2 ms from base to shoulder; these clearly-defined notches are absent from the central lough. The major change in seismic character, from strongly reflective and hummocky (Unit 1) to weakly reflective concordance (facies 2), plus evidence from Chapter 4, suggests that that this surface is unconformable and separates Units 1 and 2.

Unit 2

Facies 2: This is the lowest facies in Unit 2 (fig. 5.11), which comprises a sequence of seismically transparent, draped deposits observed in both Greyabbey and Main Channel regions. Sediment isopachs for Unit 2 in Greyabbey Bay are reconstructed in fig. 5.13. Facies 2 is consistently just 1 ms in vertical thickness and bounded by a single reflector above unconformity A. System resolution is insufficient to determine whether this facies contains evidence for internal structures. This facies is identified throughout the studied areas of the lough, as are the overlying facies 3,4,5 and 6. Seismic facies 2, 3 and 4 are extremely similar in character; they have been divided because for each of them, the upper bounding, offlapping reflector appears occupy a more basinward position. It is extremely difficult to determine whether this apparent shift represents a real phenomenon, as the upper bounding unconformity of unit 2 may have subsequently truncated each facies to produce this effect.

Facies 3: Seismically transparent and concordantly draping facies 2; of thickness c. 2 ms. This facies has been separated from facies 2 on grounds of exhibiting more basinward contact points, rather than due to differences in internal seismic character.

Facies 4: A set of characteristically similar reflectors, which conformably and concordantly drape facies 3 within basins. Reflection from each internal surface is strong; between surfaces the facies appears acoustically transparent. Moving upwards through this facies, offlap contacts shift successively basinward, although the cause of this may be erosional, as for facies 3. This facies is bounded at its upper surface by parallel, closely adjacent "twin" reflectors of c. 1 ms separation. Overall thickness of facies 4 varies from 1.5 to 4 ms, being more regionally variable than that of the underlying sediments.

Facies 5: A group of up to 5 surfaces of 1-1.5 ms separation, which overlie facies 4, but possess a more variable structure than the underlying concordant surfaces. Individual reflectors within this group appear to exhibit similar basinward shift as the underlying facies. The upper surface of this facies is identified as being the highest reflector within the unit to exhibit this shift. Above this reflector, there is a major change in stratigraphic architecture, from thin, relatively concordant facies containing sub-parallel reflectors to massive facies exhibiting incoherent internal reflections.

Facies 6: A thin (c.1 ms) deposit (fig. 5.13), whose contacts clearly overstep the uppermost deposits of facies 5, justifying its position within unit 3 rather than unit 2. The seismic characteristics of facies 6 are identical to facies 5 and markedly different to that of the overlying facies 7, comprising thin, gently undulating reflectors of generally concave-upwards cross-basinal profile, so facies 6 has been placed within Unit 2. The sub-parallel incidence of Unconformity B against facies 6, plus the thin nature of this deposit (close to the system resolution), make it difficult to determine whether facies 6 has been significantly affected by erosion (fig. 5.13) and therefore whether it lies within Unit 2 or Unit 3. Facies 6 is observed at c. -7m OD in Greyabbey Bay, which is significant to subsequent considerations of erosion surface altitude.

Unconformity B: A major unconformable surface, observed throughout the lough. Unit 2 is bounded at its uppermost surface by Unconformity B, and the apparently conformable contact between facies 5 and 6 (see fig. 5.13). Unconformity B is clearly erosive in the central and northern basins, but less clearly so in Greyabbey Bay, where it intersects unit 2 reflectors at too oblique an angle to clearly determine whether erosion has occurred. In the northern and central basins, this surface is sometimes observed cutting deeply into the sediment pile and truncating reflectors down to Unconformity A.

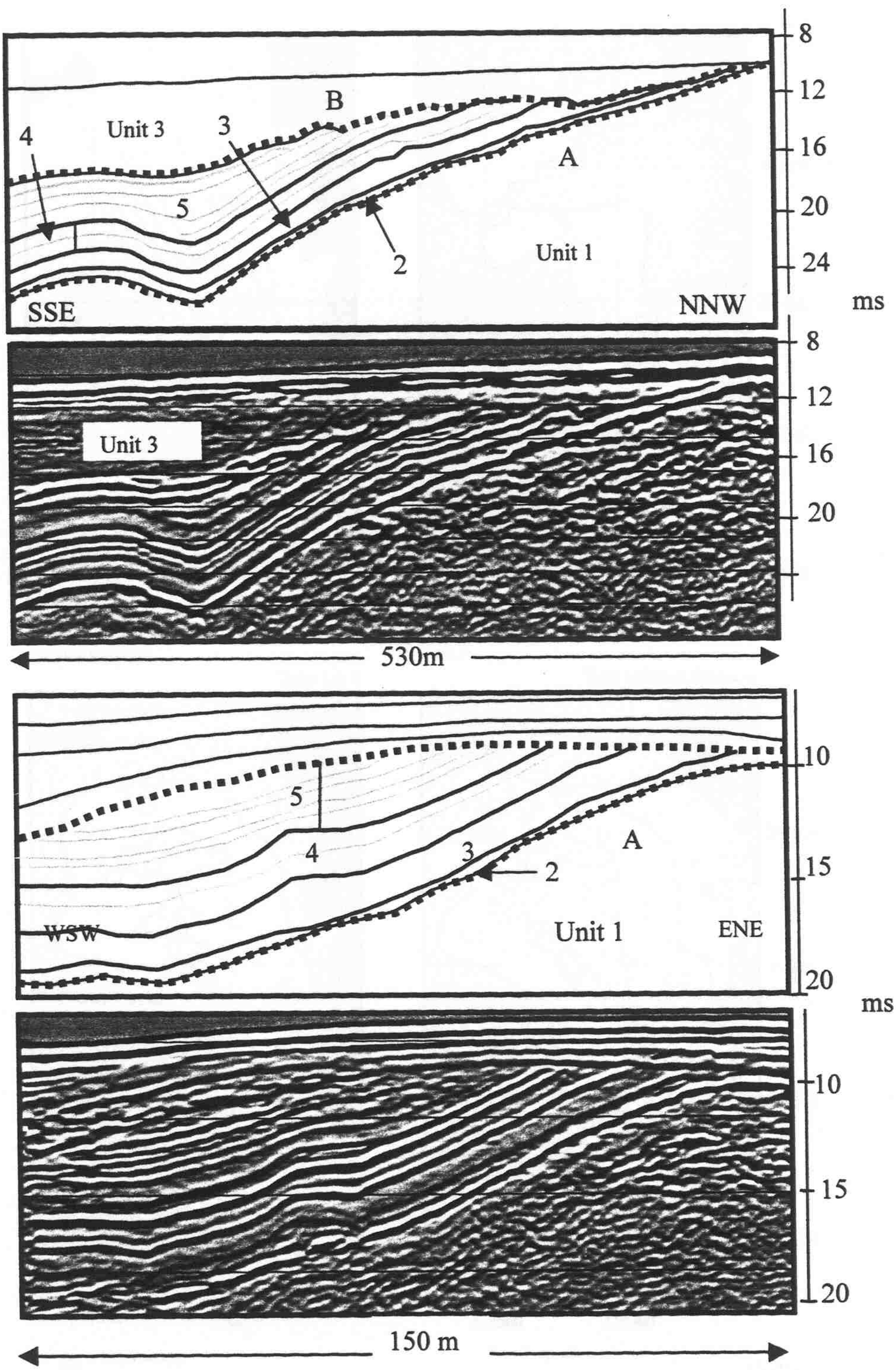


Fig. 5.11: Seismic facies 2-5 and bounding unconformities A & B. Top: Stratal surfaces in this section from Greyabbey Bay exhibit a pattern of contact relationships which may be consistent with gradual decline in RSL during late-glacial times, although the extent of erosion at unconformity B is difficult to gauge. Bottom: Elsewhere in the lough Unconformity B clearly truncates reflectors within Unit 2.

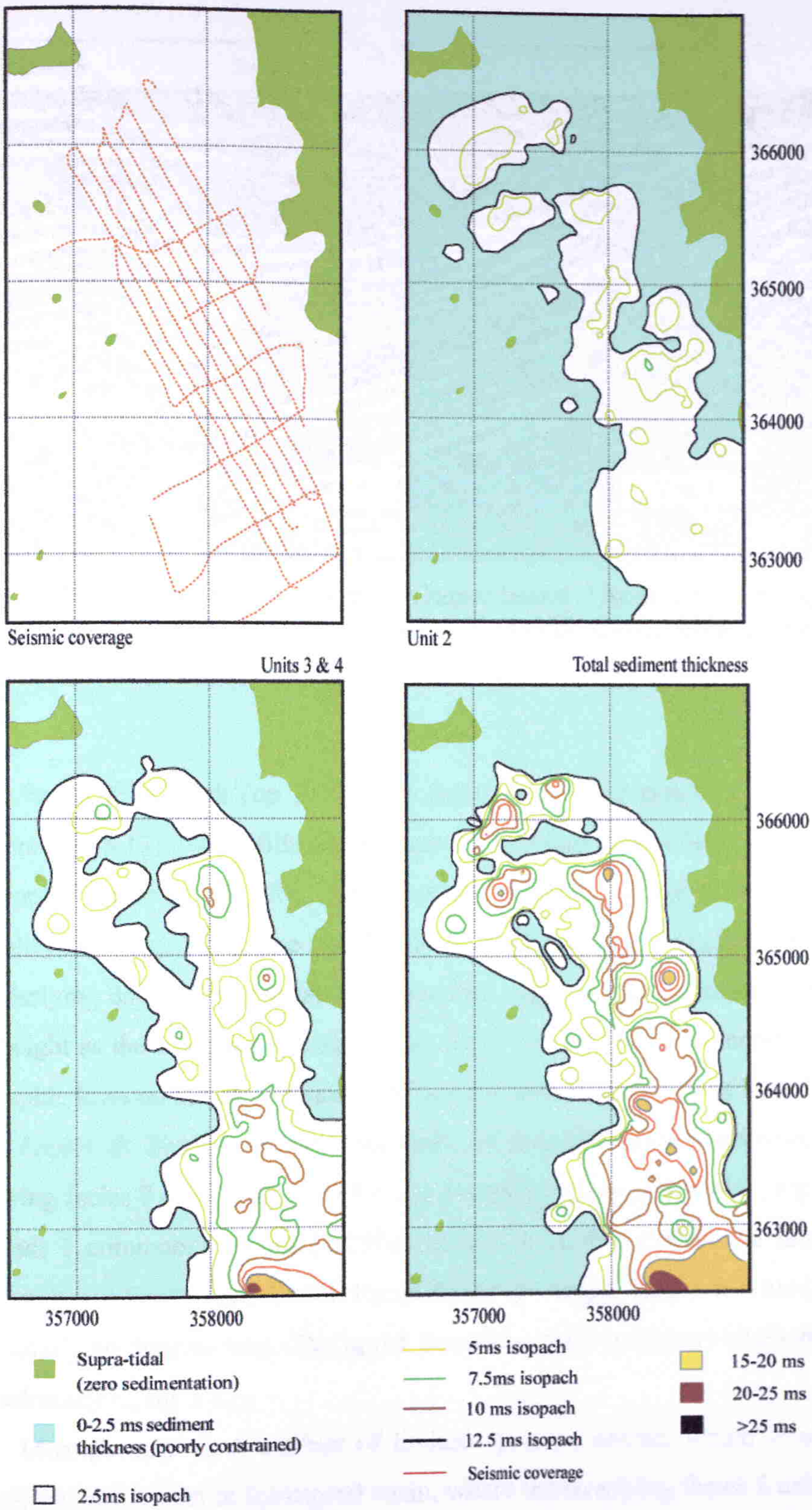


Fig. 5.12: Isopach plots (in TWTT) for Greyabbey Bay. The zero thickness isopach has been discarded as it occurs remote from the survey grid, and was poorly constrained. Contours have been generated in GMT.

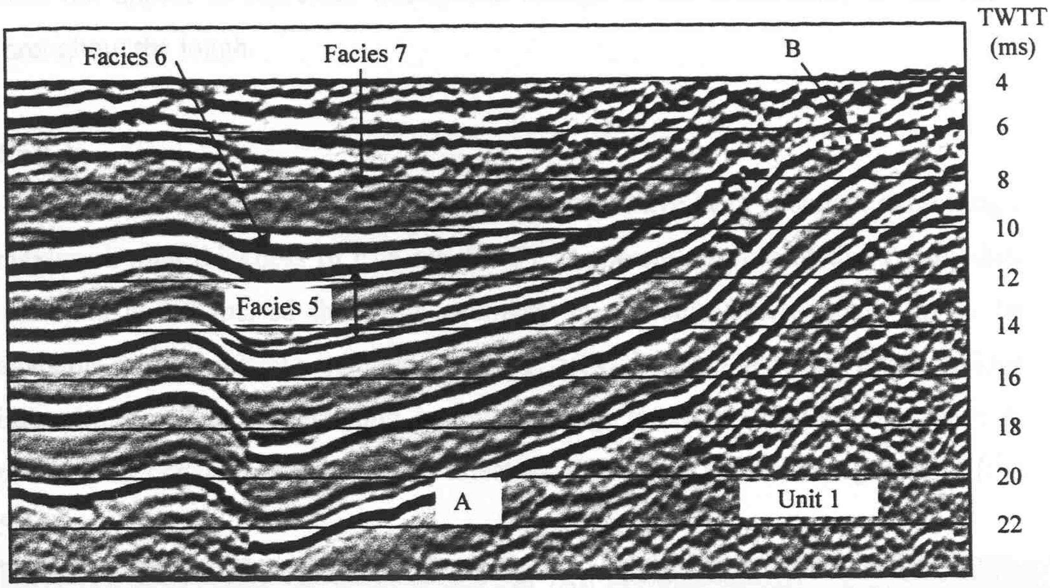


Fig. 5.13: Processed section from west of Chapel Island. The extent of Unconformity B in this region is unclear; it is difficult to determine non-conformable contacts between facies 6 and 7.

Unit 3

Facies 7: A thick (up to c.5 ms) facies containing discontinuous internal reflectors (fig. 5.13), which fills depressions in the underlying reflector topography, overstepping facies 6, and often onlapping onto facies 3 on the basin margins of Greyabbey Bay (fig. 5.11). The upper surface of this facies is rougher than that of the underlying deposits, and localised altitudinal highs on this surface can lie at the same height as the basin edge contacts (fig. 5.14). Facies thickness increases above topographic lows on the basal contact - in contrast with the deposits of Unit 2.

Facies 8: Similar in form and lack of internal seismic structure to the underlying facies 7 (fig. 5.14), but of much greater lateral extent. Onlapping contact with Unit 1 commonly occurs 50-200m further to landward than the underlying contact between facies 7 and Unit 1. Facies thickness ranges from 3 to 6 ms (thickest over underlying depressions). The upper bounding surface appears unconformable (Unconformity C, fig. 5.15).

Unconformity C: A surface of limited apparent extent, which is observed most clearly in the west of the central basin, where the overlying facies 9 exhibits an asymmetric geometry (fig. 5.15). Unlike Unconformities A, B and D, this surface does not appear to represent widespread change in the sedimentary environment throughout the lough.

Unit 4

Facies 9: The uppermost seismic reflectors have been grouped, exhibiting a maximum total thickness of c. 5 ms TWTT. Apparent spacing of these individual reflectors is 1-2 ms, so their true geometry is probably indeterminate given the available vertical seismic resolution (e.g. fig. 5.14). Internal facies attributes include intermittent reflectors persisting laterally for up to 150m. In locations close to present-day channels, this group of reflectors exhibits an asymmetric geometry (fig. 5.15)

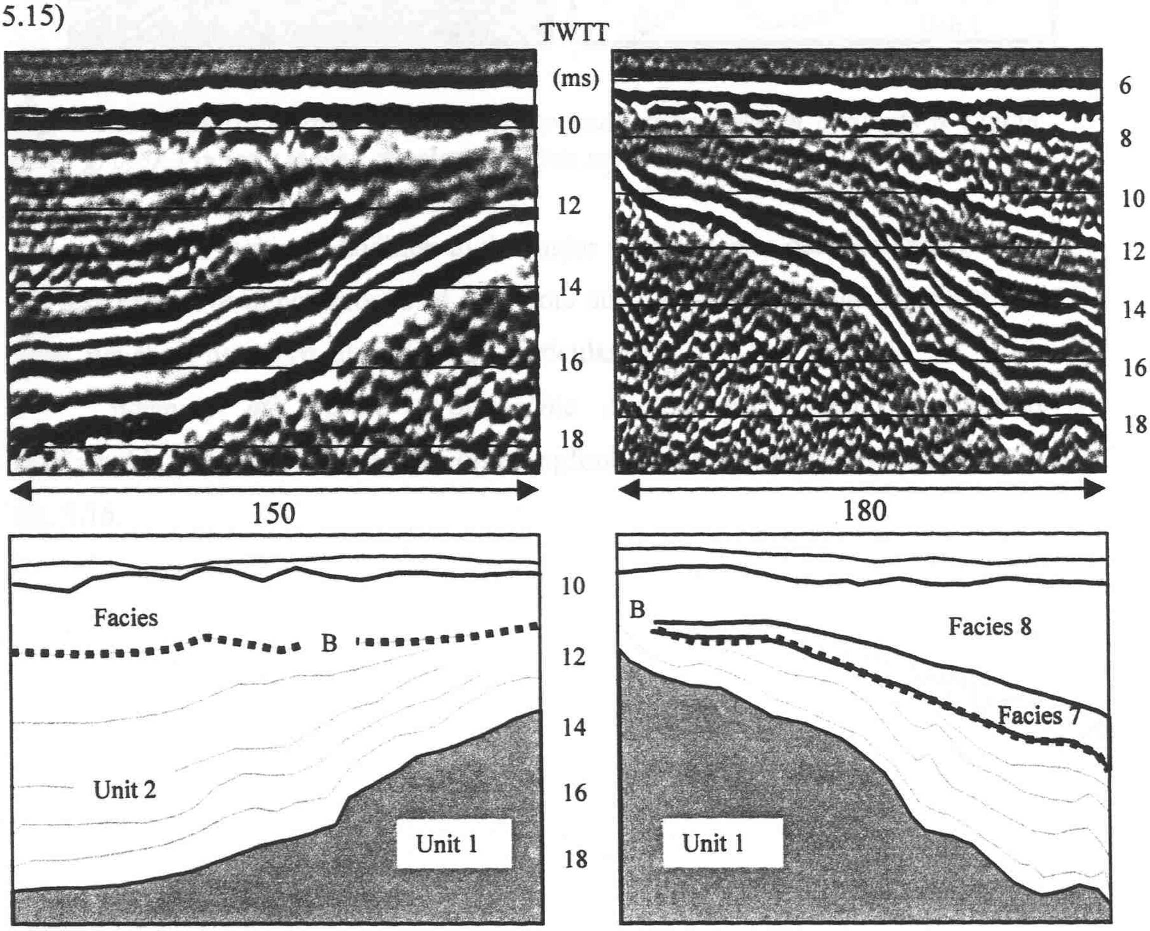


Fig. 5.14: Examples from Greyabbey Bay of facies 7 & 8.

Surface D: The present seabed, which in places appears to be undergoing erosion, and thus represents an unconformity and its correlative conformity. Where erosional, this surface truncates units down to acoustic basement in parts of the central basin, although in Greyabbey Bay it is restricted in influence mainly to facies 8 & 9.

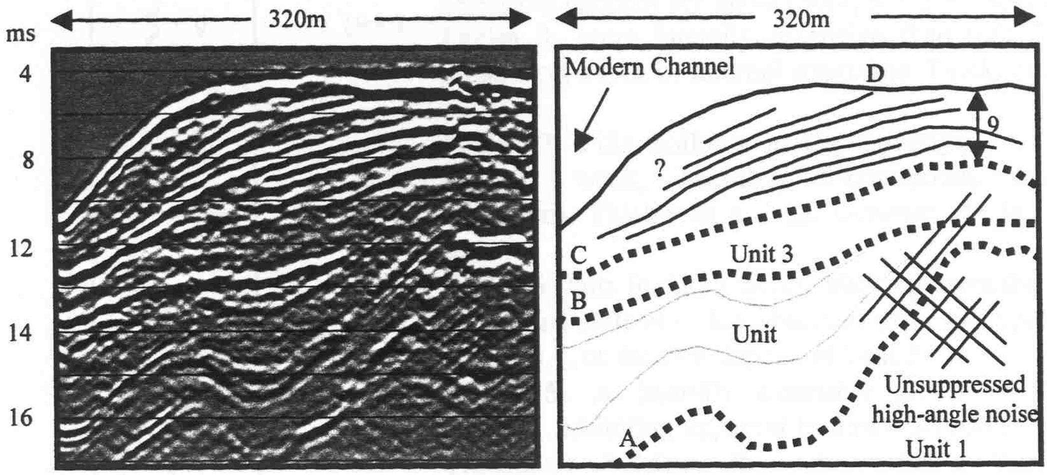
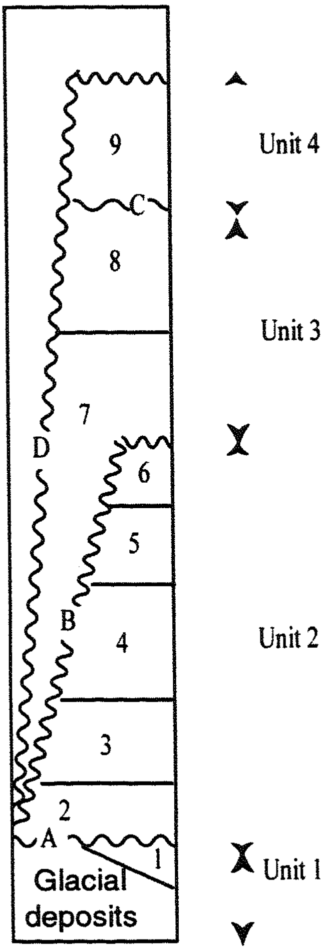


Fig. 5.15: Complex stratigraphic geometry imaged in western Strangford Lough (see fig. 5.8). Facies 9 is well developed in this section.

Further Facies: In addition to the major seismic facies detailed above, there are less extensive minor groups of reflectors such as loose material upon the sea floor, which do not merit allocation to a particular unit.

Summary of Seismic Stratigraphic Facies: An overall, synthesised stratigraphic column for the regions of Strangford Lough investigated is presented in fig. 5.16.



Facies 9: Most recent deposits. Intermittent reflectors persisting laterally for up to 150m, at 1-2 ms spacing.
Facies 8: More laterally extensive than unit 7 and possessing a lack of internal structures. Thickness: 3-6 ms.
Facies 7: Fills hollows in the underlying surface. Exhibits weak, laterally discontinuous internal reflections. Thickness: c. 5ms. Oversteps facies 3,4,5 & 6.
Facies 6: Thin (c. 1ms) facies. May represent the most basinward shift in onlap observed prior to deposition of facies 7, or the first deposit of Unit 3.
Facies 5: A laterally extensive group of stratal surfaces exhibiting apparent basinward-shifting onlap. Thickness: 5-7.5ms & more variable than the underlying facies.
Facies 4: Group of similar, draped surfaces. Thickness: 1.5 to 4ms.
Facies 3: Concordantly drapes facies 2. Thickness: 2ms
Facies 2: Basal member of Unit 2. Thickness: 1ms
Facies 1: Rarely observed. Contains weak internal stratification. Thickness: up to 5ms.

Fig. 5.16: Summary seismic stratigraphic column for the regions of Strangford Lough investigated.

5.11: Shallow Gas.

The presence of small volumes (<1%) of shallow gas commonly results in the phenomenon of acoustic "blanking", which has been described from many nearshore localities around the UK and Irish coasts (Davis 1992). Around the UK and Irish coasts the only gas present in significant quantities is methane (Davis, 1992), which originates mainly from decomposition of organic materials within post-glacial deposits, but can also migrate up from deeper sources via cracks in the underlying rockhead (Taylor, 1992). Shallow gas is often mobile (Judd & Hovland, 1992); reflections from gas bodies commonly step up and down between stratal surfaces.

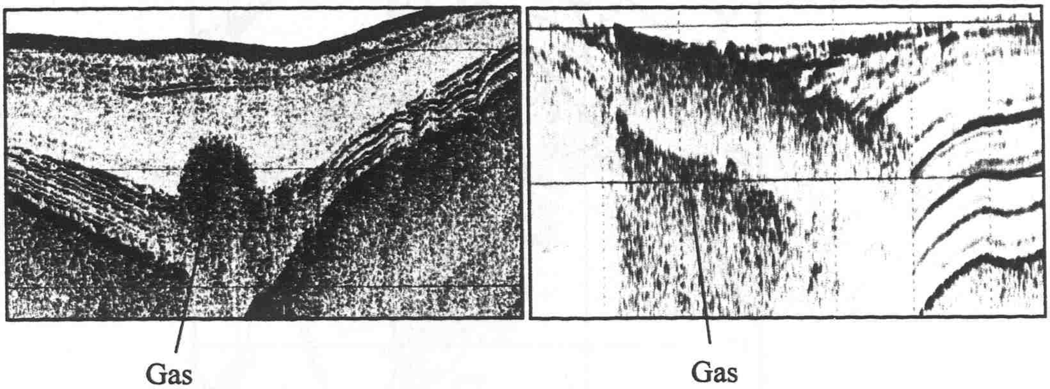


Fig. 5.17: Shallow gas, cross-cutting the sedimentary stratigraphy in Greyabbey Bay (left), and the northern basin (right), Strangford Lough.

Shallow gas has been identified on numerous profiles within Strangford Lough; basinal regions are unaffected, whilst gas is common in near-shore sediments, where it entirely masks the late-glacial stratigraphy. No gas is observed within seismic facies 1 through to 6. Above this, the gas distribution falls within two modes. Within facies 7 & 8, gas occurs above depressions in the underlying surfaces (fig. 5.17), whilst in facies 9 it is sometimes observed as forming a shallow layer running parallel to the seabed.

5.12: Correlation of seismic, outcrop and borehole data.

Lack of core data from within the survey area prevents direct ground truthing of the seismic data, however, information concerning the type of sediments deposited within the wider lough basin is available from the published literature (section 5.2) and the unpublished Northern Ireland Dept. of Works core archive. The closest archived site is 6km NW of the study area; although distant, the reports do provide valuable information upon sedimentation within the northern reaches of the lough (fig. 5.18). The cores described often penetrate through the lough sediments to the Triassic sandstone basement, which forms an irregular surface at between -13 and -18m OD beneath Newtownards Airport (GR 3491 3730). Cross-correlation of the entire core database (c. 2000 borehole logs and test pits) by Dr R Kalin of Queen's University, Belfast (pers. comm. 1998) shows this depth to be approximately constant beneath the shores of the northern basin.

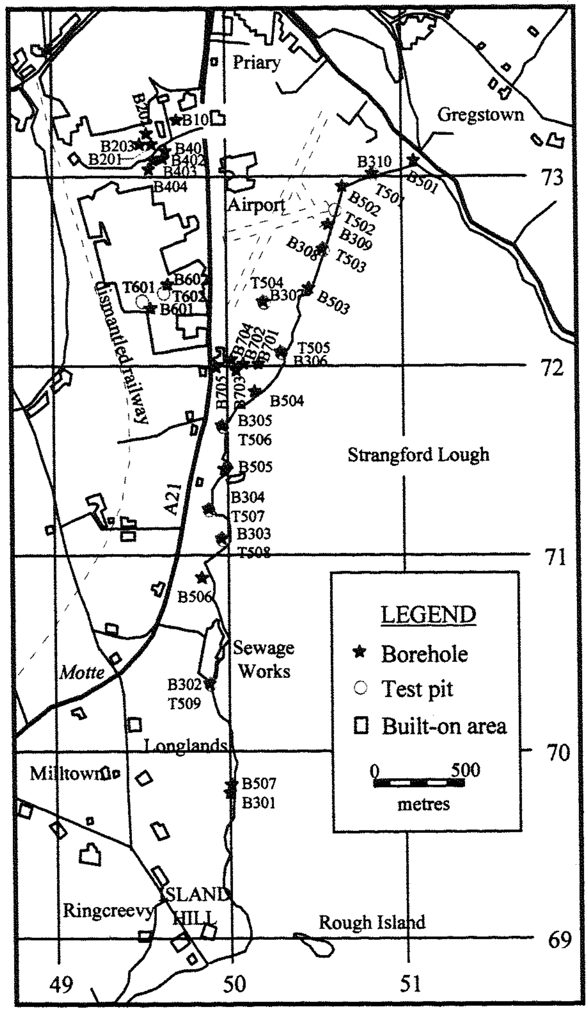


Fig. 5.18: Location of boreholes around the north coast of Strangford Lough relevant to this survey, courtesy of Mr D. Glynn, Dept. of Works, N.I. Co-ordinates refer to grid squares on the OS NI 1:50 000 sheet 21.

The original borehole logs were produced by several different geotechnical engineers, and contain only a basic sediment classification and description. Six broad units (U, V, W, X, Y & Z) have been identified from the local borehole information (fig. 5.19).

Borehole Unit	Description & Interpretation	Seismic Strat. Equiv.	Approx. Age
Z	Loose, dense fine-or-silty sand. Upward brown to grey colour change, contains occasional shells. Commonly grades up into organic-rich silt. Origin of shells not ascertained. Max. thickness 8.8m (B401). Overlain by anthropogenic fill. Maximum elevation of upper surface is +2.85m OD	Unit 3	Post-glacial
Y	Soft to v soft grey-brown organic clayey silt containing occasional shells. Origin of shells not ascertained. Observed only beneath shoreline core sites - absent inland. Max. thickness >10m in borehole B306. No sand laminations.	Unit 3	Post-glacial (<9500 BP?)
X	Soft to firm brown silty clay containing laminations and lenses of sand towards base. No organics. Max proven thickness 7.5m. Upper contact limits -11m to +0.63m OD. Lowest beneath lough shore.	Unit 2	Late-glacial
W	Stiff sandy, gravelly, silty red-brown clay with cobbles, boulders & sand lenses. Interpret as upper till unit. This unit is not always present.	Unit 1	>14700 BP
V	Thin (1m) layer of gravel. Seldom present - possibly fluvio-glacial.	Unit 1	?
U	Triassic Sherwood sandstone.	N / A	N/A

Fig. 5.19: Correlation of borehole data from the northern shores of Strangford Lough with seismic data and published outcrop descriptions.

Descriptions of marine mud ("Red Marine Clay") from the Ards and Lecale peninsulas (Morrison & Stephens (1965), Devoy (1983), Stephens & Collins (1961), Stephens (1963) and Singh & Smith (1973)) suggest correlation with borehole unit X. This unit is generally described as a stoneless sandy silt/clay containing sandy laminations, but may be quite spatially variable in composition. McCabe (1996) describes marine mud AMS ^{14}C calibrated to 15246 ± 229 yrs BP on Rough Island (fig. 5.23). There is no visible or reported physical barrier dividing this site from the airport boreholes, therefore a cross-site correlation with the brown silty clays of borehole unit X appears valid. The nearest recorded example of this deposit is 1 km north of Rough Island (fig. 5.23). Similar marine muds have been described from widespread localities including Lecale, the eastern Ards Peninsula and NW Strangford Lough.

Borehole unit X comprises lenses and laminations of sand within soft silty clay. Such an arrangement might provide a strong basal acoustic contrast by juxtaposition of silty clays with glacial tills, whilst sandy laminae could produce the appearance of the thin (sub-resolution?) laminae observed in seismic facies 4, 5 and 6 of the chirp data. It is proposed that seismic facies 2 to 6 are nominally represented by the deposits described within Borehole unit X. Seismic data suggests that unit 2 represents falling RSL, with a consistently offlapping seismo-stratigraphic architecture. It is therefore possible that the higher facies of this group were either not deposited in the cored region, or removed by erosion associated with unconformity B. The marine muds of Strangford Lough have been dated from coastal exposures at 16623 ± 258 yrs BP (Killard Point), 16429 ± 253 yrs BP (Killard Point) and 15246 ± 229 yrs BP (Rough Island) (all McCabe 1996). These dates suggest that seismic unit 2 is late-glacial in age, but provide no control for individual seismic facies.

Borehole Unit X and seismic unit 2 are interpreted as late-glacial deposits, truncated by major unconformity B. Established RSL curves (fig. 5.1) indicate that this erosion can be explained if unconformity B represents the effect of low RSL during the early Holocene. Above seismic unit 2 and borehole unit X, a marked contrast in the nature of the deposits occurs, suggesting a marked change in the depositional environment. In seismic section, a transgressive massive layer (facies 7) containing occasional laterally discontinuous internal reflectors replaces the previous pattern of thin laterally-continuous surfaces. Facies 6 has been assigned to Unit 2 on grounds of similarity with facies belonging to this unit, but it is impossible to separate from Unconformity B, prompting suggestion that facies 6 is the correlative conformity to this unconformity. Unconformity B is observed at greater depths than facies 6 (observed at c. -7m OD in Greyabbey Bay), therefore they are not correlatable, and facies 6 remains in Unit 2. Core descriptions report organic clayey silt containing occasional shell material and pockets of clay, sand and organics (unit Y) overlying the shell-less inorganic silty clay of unit X.

Locally, post-glacial deposits are generically known to academics as the "Estuarine Clay", and to civil engineers as "sleech" (Smith *et al*, 1991), which consists of unconsolidated clays, silts and sands. The maximum proven thickness of this deposit in the Newtownards area is 18.75m (Smith *et al*, 1991), where it comprises red-brown silty clay, overlain by a dark brown organic silt. At Blackstaff Bridge (GR 3603 3596), immediately south-east of Greyabbey Bay, a 0.91m sequence of Estuarine Clay overlain by alluvial deposits has been described (Smith *et al*, 1991). At Ringneill Quay (GR 3514 3653), Stephens & Collins (1961) describe a marine "Estuarine Mud": a dark grey mottled sandy silt or clay containing marine shells and seaweed. This is inferred to represent the onset of the early Holocene post-glacial RSL recovery. Singh & Smith (1973) describe shelly organic Estuarine Clay from Woodgrange, Lecale (GR 3439 3445) overlying an organic deposit, in an inter-drumlin hollow. Nearby, the Estuarine Clay overlies peat deposits containing large oak trunks. The clay is proposed to represent early Holocene recovery in RSL, following deposition of organic material in a non-marine environment.

Borehole unit Y appears very similar to the Estuarine Clay. It seems likely that unit Y - which is better developed in boreholes to the east of the airport - represents deposits from the incoming post-glacial marine transgression. It is interesting that no gas blanking is observed beneath unconformity B, but above this surface such reflection is commonplace. Borehole unit Y contains significant amounts of organic material; it is possible that this organic material provides the source for the extensive shallow gas banks observed in seismic section.

Borehole data and field evidence suggest that seismic unit 2 may correlate with borehole unit Y, which represents deposits from the post-glacial Estuarine Clay. This clay consists of soft organic clayey silts. There is no indication of a bipartite division of the lower post-glacial deposits from any of the borehole data examined, however, so the cause of the distinct reflection between facies 8 and 9 is unexplained.

At many of the sites discussed above, the Estuarine Clay is overlain by beach sand, gravel or alluvium. Borehole unit Z is generally coarser than unit Y, possibly reflecting transition to a higher-energy depositional environment. Borehole unit Z deposits lie up to +2.85m OD, suggesting deposition during the middle Holocene RSL maximum described by Carter (1982)(fig. 5.1). Lower altitudes (i.e. greater water depths) in the seismic survey area suggest that the depositional environment of unit Z contrasted strongly with the prevailing basinal conditions further offshore. Thus borehole and seismic data representing mid-Holocene deposition cannot be correlated and information relating to facies 9 is anecdotal. Local divers (Magorrian pers. comm.) report that the present seabed south of Mahee Island (*chapter 6*) consists of soft and easily resuspended material, in agreement with published RoxAnn data (Magorrian *et al,* 1995).

Summary of Correlation

Correlation of the seismic and borehole data with widespread field descriptions from around the lough shores suggest that Unit 2 represents late-glacial deposits comprising shell-less inorganic silty clay, which contains sandy laminations ("Red Marine Clay"). The upper bounding surface of this unit is unconformity B, which represents subaerial or shoreface erosion caused by a gradual decrease in RSL toward the early Holocene minimum. Unconformity B is overlain by post-glacial unstratified organic clayey silt containing occasional shell material and pockets of clay, sand and organics ("Estuarine Clay"). It is proposed that seismic unit 3 represents the Estuarine Clay. High RSL during the middle Holocene precludes correlation of seismic and borehole data; the relationship between units 3 and 4 is not clear from the evidence discussed above, but will be further discussed. The present seabed is a surface (D) representing both an erosional unconformity, within some areas of the central and northern basin and a surface undergoing active deposition in Greyabbey Bay. Seabed composition ranges from sand on the shore of Greyabbey, to very soft and easily resuspended silts in the northern and central basins.

5.13: Extraction of 3D Surfaces From High-Resolution Seismic Data

The 1997 seismic survey of Strangford Lough provided 2D information upon subsurface sedimentary structure. Improved knowledge of the spatial variation in sediment distribution in 3 dimensions can be gained by digitising the interpreted 2D sections, correcting for tidal effects[6] and fitting a 3D surface to the resultant data in GMT (Generic Mapping Tool) software[7] (Wessel & Smith, 1990).

Only sediment volumes well constrained by seismic coverage can be examined by reconstructing 3D surfaces in the method described; otherwise interpolation produces spurious results. Constraint can also be degraded by erosional truncation of reflectors or by shallow gas blanking.

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[6] The tidal curve was assumed as approximately linear for the duration of each seismic line (c. 20 minutes). Vertical offset from Belfast Datum was converted to effective TWTT in sea water (V_p = 1481 ms^{-1}) for the ends of each survey line, and tidal corrections were interpolated during combination of digitised TWTT and DGPS data. This method assumes that the gauge on Mahee Island (fig. 5.6) accurately reflects changes across the entire survey area. Local experience suggests that high tide reaches Mahee Island approximately 20 minutes after it passes between Strangford and Portaferry. Kirk, McClure & Morton (1991) measured and modelled the tidal circulation for all states of the tide. Unfortunately, this report contains contradictions the author considers its contents unreliable. In the absence of a reliable scientific means of correcting for lateral variability in tidal height, no laterally-variable correction has been made, but a maximum tidal error for the entire seismic data set is estimated at $\pm$ 0.17m.

[7] A short piece of software capable of marrying the navigation database to the digitised TWTT information was written; this solved the problem of incompatibility between the navigation, digitising and tidal data formats. An additional correction to the DGPS data was made at this stage; the data was found to contain a small scale (c. $\pm$1m) "wobble" which was approximately sinusoidal, and could be quickly removed by running a five-sample mean through the raw DGPS output file.

Greyabbey Bay

In Greyabbey Bay, three surfaces have been reconstructed: Unconformity A, Unconformity B and its correlative conformity, and the present seabed. This creates a broad division between what have been interpreted as the late- and post-glacial deposits. For spatial constraint it was necessary to use Admiralty Chart information (Sheet no. 2156) regarding the surrounding supra-tidal topography, and to make simplifying assumptions based on visits to shorelines within the locality. Till is often exposed within the intertidal zone of Strangford Lough, corresponding to zero late- and post-glacial sediment thickness in this area. For the purpose of this model, it is assumed Unconformity A represents the seabed between MHWS and MLWS, and that Unconformity B is also constrained by these limits. The assumption of coincidence between Unconformity A and the present seabed is broadly justified at the high water springs mark. The assumption that this overlap extends to MLWS sets the thickness of the intertidal deposits outside of the coverage area to zero. Ryan & Cooper (1998) describe the intertidal zone of Greyabbey Bay as comprising a thin veneer of recent sands overlying a wave-cut platform of glacial deposits. The separation between the survey grid margins and the surrounding MLWS isobath greatly exceeds any probable error in intertidal sediment thickness, therefore resultant effects upon interpolation within the grid should be minimal.

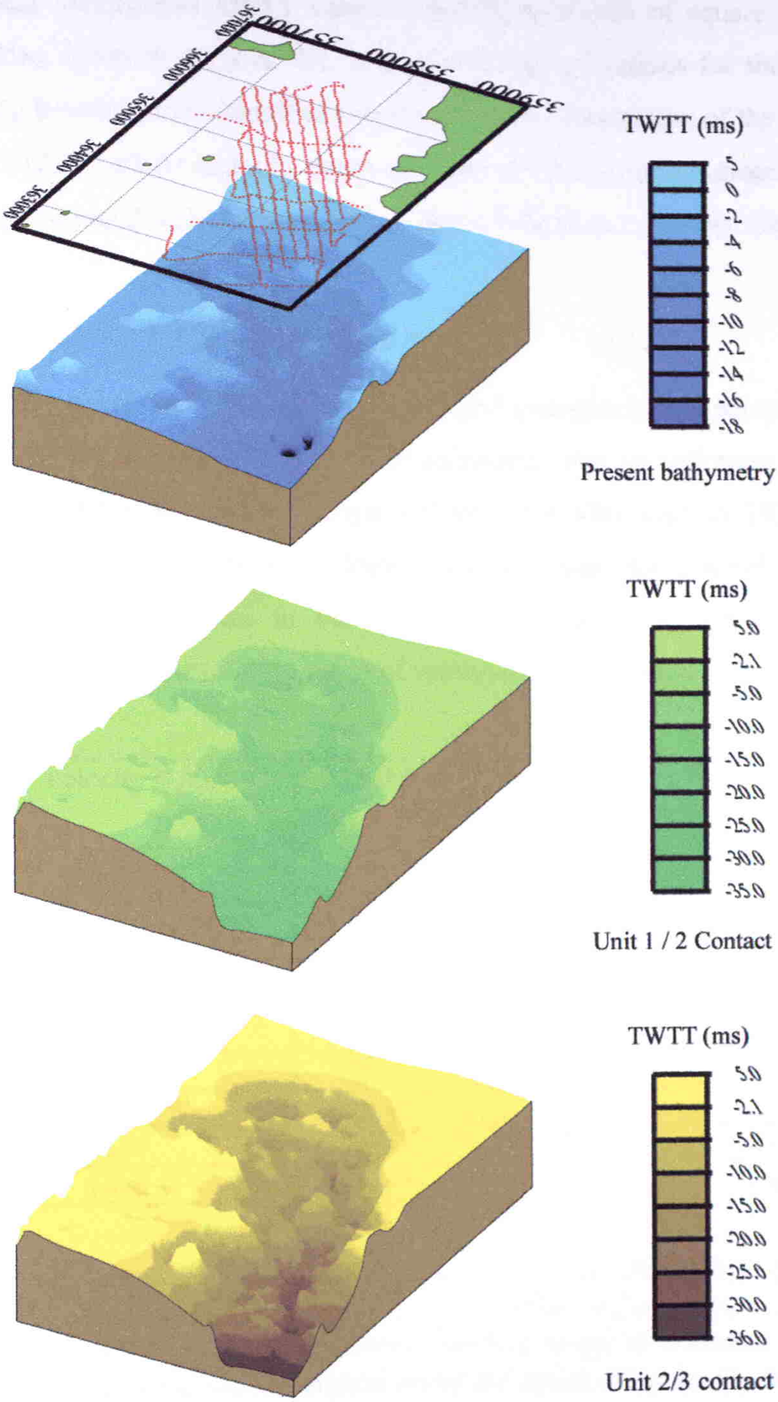

Fig. 5.20: 3D GMT reconstruction of major seismic reflection surfaces in Greyabbey Bay. Additional bathymetric control was provided by Admiralty Chart 2156 (1976); all values are TWTT relative to OD.

3D surface reconstruction over the survey grid in Greyabbey Bay (fig 5.20) provides insight upon basin development within the shallow to intermediate-depth areas of this relatively sheltered embayment. 3D surfaces were constructed from digitised and interpolated TWTT values assigned to a grid of square bins (side length I=25m, limits N, E, S & W). A range of approximations for the sediment volume (V_S) between unconformities was calculated by summation of the difference in surface TWTT (Δt) for each bin, depth-conversion of total contributions at a range of suitable compressional wave velocities, and multiplication by the bin area (I^2) thus:

$$V_s = \left[\sum_{S}^{N} \left[\sum_{W}^{E} (\Delta t) \right] \right] * 0.5 * V_p * I^2 \qquad (5.1)$$

Depth conversion of TWTT from late- and post-glacial bounding reflectors has been made, using seismic velocities for continental terrace sediments suggested by Hamilton (1971), which range from 1519ms^{-1} for silty clay to 1836ms^{-1} for coarse sand. A mean velocity of 1685ms^{-1} has been used for general statements regarding sediment volumes, in the absence of ground truthing information. Calculated sediment volumes for a range of velocities are presented in fig. 5.21.

Velocity V_P (ms^{-1})	Unit 2 (x 10^4 m^3)	Units 3 & 4 (x 10^4 m^3)	Total Volume (x 10^4 m^3)
1519	2581	1230	3811
1550	2634	1255	3889
1600	2719	1296	4015
1650	2804	1336	4140
1700	2889	1377	4266
1750	2973	1417	4390
1800	3058	1458	4516
1850	3143	1498	4641
1685	**2900**	**1300**	**4200**

Fig. 5.21: Calculated approximate sediment volume in Greyabbey Bay, using conversion velocities cited by Hamilton (1971). The sediment type and mean compressional wave velocity are unknown, hence a range of potential values for sediment content is calculated. Variation about the mean calculated volume is c. ± 10 %.

Calculations suggest that the total volume of sediment deposited in the 6 km^2 survey area of Greyabbey Bay is c. 4200 x 10^4 m^3 ± 10 %, splitting into c. 2900 x 10^4 m^3 for unit 2 and c. 1300 x 10^4 m^3 for units 3 & 4. This division is based upon the interpretational convention that the boundary between units 2 & 3 is marked either by Unconformity B, which occurs above facies 6, where this facies is present.

The variation in sediment distribution within Greyabbey Bay (fig. 5.20) may be a function of two controlling factors. The thickest sediment accumulation (c. 15m) lies in the south-east of the bay, and may be related to the underlying presence of the Newtownards Fault, which Smith et al (1991) describe as running offshore close to Herring Bay (GR 3585 3653). In the north, basin alignment is parallel to the NNW-SSE direction of drumlin-forming ice flow inferred from aerial photography and field observations in north-east Ireland (Hill & Prior 1968, McCabe & Clark 1998). This alignment agrees with primary evidence for ice flow direction, (striae, clast, drumlin and moraine orientation) and supports the suggestion that the uppermost facies of unit 1 is the drumlinised till unit described by Hill (1968).

It is impossible to gauge the timing of sedimentation within Greyabbey Bay without local correlative core data. A rough estimate based upon a late-glacial period of 15000-9500 BP suggests average sedimentation rates of c. 1.2mmyr^{-1} for both late- and post-glacial deposition in the thickest basinal deposits. This value is an underestimate, as it assumes constant deposition without hiatus or erosion.

The Northern Basin

Seismic data from the northern basin of Strangford Lough (fig. 5.7) suggests a greater distribution of shallow gas than that observed in Greyabbey Bay. The sedimentary record in this area is also less complete, as Unconformities B & C erode and truncate to greater and more varied depths across the region. It is difficult to isolate Units 2 and 3 sufficiently to produce an accurate 3D reconstruction, so instead only the upper surface of Unit 1 and the present seabed have been digitised (fig. 5.22). The pattern observed is similar to that of Greyabbey Bay: the topography of Unit 1 is greatly subdued by overlying sediment. Sediment distribution favours marginal sites around Chapel Island and Bird Island, and the northern area of the survey grid, where Admiralty data indicates that the lough shelves rapidly to depths of less than 10m. Lack of data in the extreme north-west of the survey grid has produced a broad interpolation artefact. The corresponding suggestion of large sediment thicknesses is unreliable, although shorter wavelength overlying peaks in this area are supported by the seismic data.

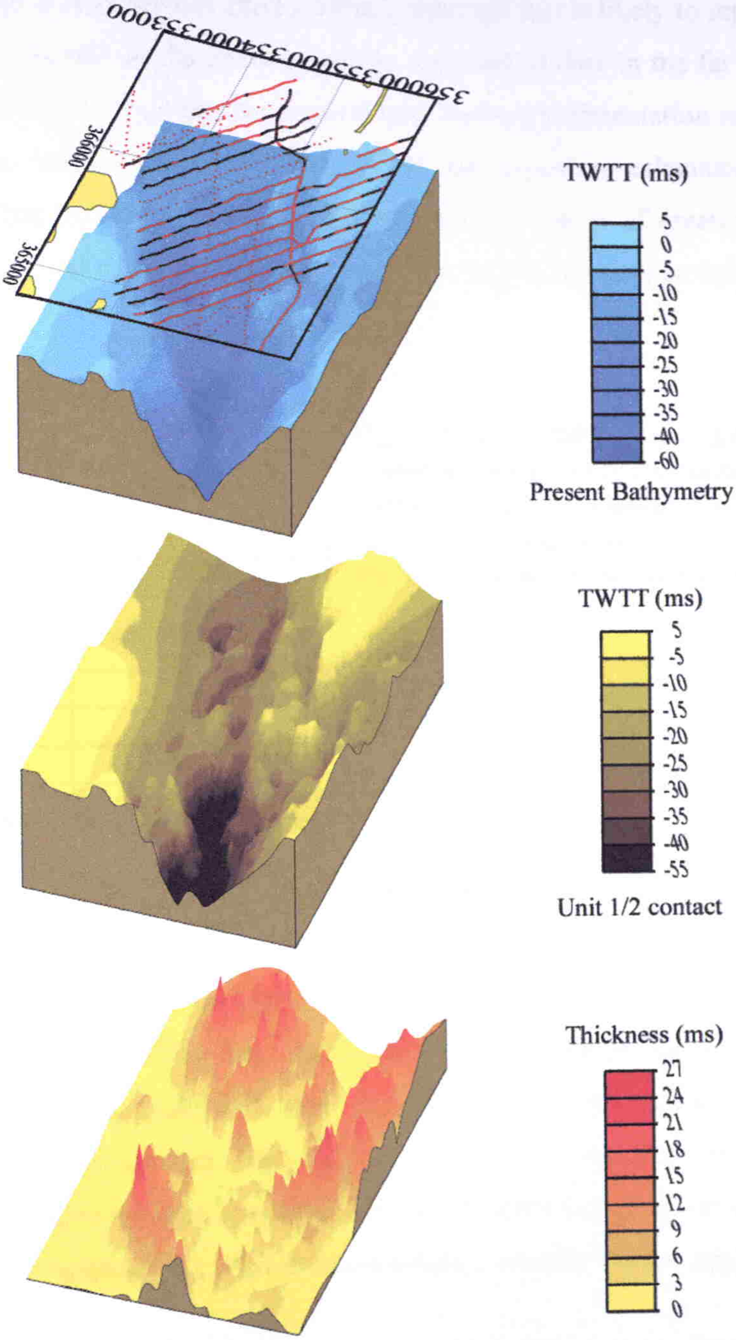

Fig. 5.22: 3D interpolated surfaces from the northern basin of Strangford Lough. Top: Present seabed. Middle: Upper surface of Unit 1. Bottom: Total sediment thickness plot for this region, indicating the location of inter-drumlin depocentres (discrete spikes) and the effect of poor seismic constraint (broad dome at top of plot).

Calculation of total sediment volume for the northern basin (fig. 5.23) is handled in similar fashion to that in Greyabbey Bay. The mean approximate sediment volume is calculated as 2862 x $10^4 m^3$, although this is likely to represent a significant overestimate, as the effect of poorly constrained data in the far north of the region is difficult to quantify. An approximate average sedimentation rate based upon maximum basin sediment thickness in the north-west is calculated as 1.5 $mmyr^{-1}$. Distortion by interpolation artefacts is probable; a value of greater relative accuracy from several other basins is 1.2$mmyr^{-1}$ - which is identical to values from Greyabbey Bay.

Velocity V_P (ms^{-1})	Sediment Volume (m^3 x 10^4)
1519	2581
1550	2634
1600	2719
1650	2804
1700	2889
1750	2973
1800	3058
1850	3143
1685	**2862**

Fig. 5.23: Calculated approximate sediment volumes for the section of the northern basin surveyed during 1997. Velocities for depth conversion are within the range suggested by Hamilton (1971).

5.14: Incisions cut into Unit 1 throughout Greyabbey Bay

A series of V-shaped incisions have been identified in the smooth upper surface of Unit 1 in Greyabbey Bay (fig. 5.24). These features are approximately 1 to 2m deep, 10-25m in width, and occur on the flanks of depressions in the till surface at heights of between -20.5 and -8m OD[8]. The features are laterally discontinuous between adjacent lines, and are concordantly draped by the overlying facies 2 deposits without any visible intermediate deposits, which might imply channel fill.

The origin of these incisions is unclear. Four possible mechanisms for their formation are: erosion by subglacial meltwater, grooves cut into the till during the passage of icebergs calved from a tidewater (floating) ice margin, erosion by

[8]Depth converted assuming average V_P of 1685ms^{-1}

subaerial surface drainage following deglaciation, or the creation of pockmarks as a result of fluids escaping from the underlying material.

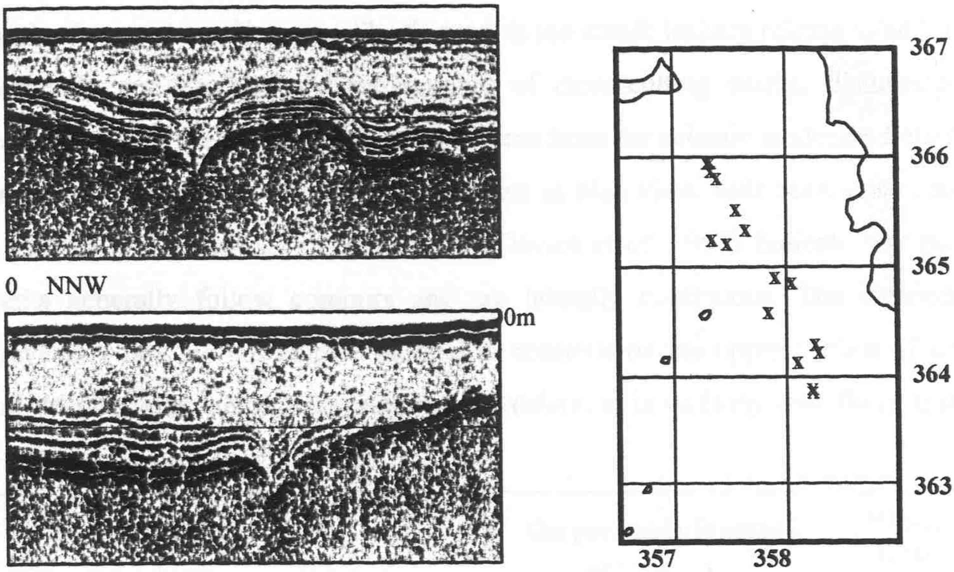

Fig. 5.24: Incisions cut into Unit 1, Greyabbey Bay (left). Unprocessed data is presented because the f-k filtering algorithm employed in processing removes events possessing relatively high dip angles. Right: location of incisions is indicated by "x".

If these incisions reflect fluvial drainage, then channels appear to terminate in inter-drumlin hollows from which there is no corresponding outflow passage. A subaerial fluvial origin also requires that sea levels lay below -16m OD at the start of the late-glacial, whilst McCabe (1997) describes sea levels of c. +25 m OD during ice retreat.

It is possible that these features were cut by combined englacial and subglacial meltwater flow. The model proposed for drumlin formation in Strangford Lough (chapter 4) requires significant meltwater volumes, so the presence of conduits is compatible with this view. A network of conduits would require connectivity rather than terminating in inter-drumlin hollows, although it could be argued that these apparent terminations might be explained by englacial uplift of meltwater. There is, however, no seismic evidence for large-scale dumping of sediment within the channels, to be expected as a result of decreasing channel competence in the sediment-rich glacial environment.

Iceberg scour is known to carve incisions into the seabed (Long, 1992). The scale of the incisions is concomitant with icebergs of c. 30-40m thickness requiring an RSL of c. +20 to +30m OD (Kenyon, pers. comm. 1999). These depths are comparable to those suggested by McCabe (1997) and conducive to deposition of late-glacial marine clays. The major arguments against this mechanism are twofold.

Firstly, the number of incision-like features is too small; iceberg release would occur seasonally and produce a large number of cross-cutting marks, disturbing the seafloor to a far greater degree than is evident from the seismic evidence. Secondly, the scour marks do not appear to be elongate in plan view. Side scan sonar records of iceberg plough marks in deep water (Davies *et al*, 1997) indicate that plough marks generally follow contours and are laterally continuous. The incisions in Greyabbey Bay are not aligned parallel to contours on the upper surface of Unit 1 and do not form continuous features. Therefore, it is unlikely that these features resulted from iceberg ploughing.

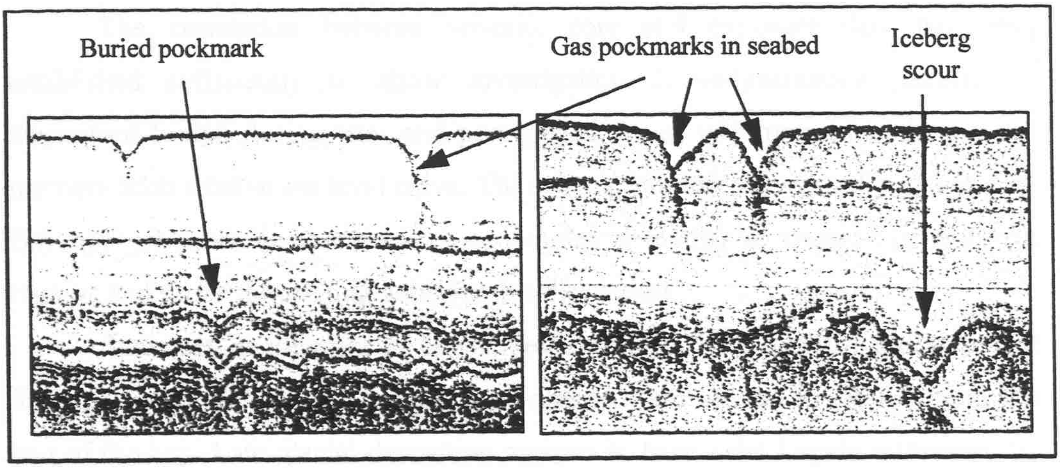

Fig. 5.25: Seismic (Huntec deep-tow boomer) evidence for gas pockmarks and buried iceberg plough marks in the Witch Ground Formation, central North Sea (reproduced from Long, 1992). Pockmarks shown are 50-100 m across and up to 2m deep.

Judd & Hovland (1992) and Long (1992) present seismic images of pockmarks formed by erosion of seabed material during fluid expulsion, which appear similar to the features observed in Greyabbey Bay. No shallow gas has been observed within Units 1 or 2, suggesting a lack of active gas migration from beneath this level. If these features *were* caused by gas escape through the Unit 1 till, all migration must have ceased before deposition of Unit 2. The source of such gas is problematic; organic material within and predating the late Midlandian glacial deposits is rarely reported, despite extensive fieldwork. Hill (1968) found no evidence for organic deposits within the tills around Strangford Lough. A deeper (bedrock) origin does not explain why release should abruptly end prior to Unit 2 deposition.

Pockmark formation can also result from porewater release, driven by hydrostatic pressure. The main Irish ice mass might provide sufficient hydraulic head to drive such a process, whereby inland migration of the escape zone would occur prior to deposition of the overlying marine drape. This hypothesis fits the seismic and environmental evidence better than its rivals and is tentatively proposed to explain these features.

5.15: Late-Glacial Sedimentation and RSL in Strangford Lough

The correlation between seismic, core and exposure data has been established sufficiently to allow investigation of sedimentation patterns in Strangford Lough during late- and post-glacial times, with respect to the general northern Irish relative sea level curve. The seismic stratigraphic record in Greyabbey Bay appears more complete and less complex than that of central and northern regions and forms the starting point for this discussion.

Sediment distribution in Greyabbey Bay (fig. 5.12 & 5.20) indicates that during late-glacial times, the major depo-centres were located in the northernmost end of the bay. Late-glacial deposition appears to have been largely influenced by the location of inter-drumlin hollows; individual basins contain up to c. 7.5m of late-glacial deposits. Late-glacial sediments (unit 2) form a draped sequence whose architecture suggests gradually falling RSL during late-glacial times. The offlapping pattern of contact points for each successive surface, suggested by the seismic data, is in agreement with the regional RSL curve (Carter, 1982). However, it is impossible to determine the effect of Unconformity B upon these contacts, due to the oblique angle of intersection between this unconformity and the unit 2 stratal surfaces (fig. 5.26). It is also possible that facies 6 represents material washed from unit 2 during subaerial or shoreface erosion, rendering this unit correlative with unconformity B.

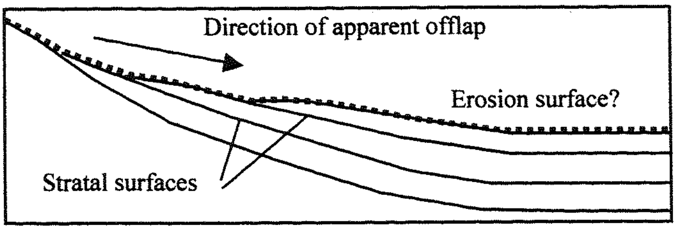

Fig. 5.26: Explanatory diagram indicating how the apparent pattern of offlap within seismic unit 2 might also be explained by erosion of material on a surface which intersects sedimentary layering at a highly oblique angle.

If it is assumed that the observed pattern of apparent offlap reflects late-glacial RSL fall, then this might offer potential for the study of regional differences in isostatic recovery, reflected in stratigraphic contact heights. Contacts for all facies in unit 2 occur at greater heights in northern Greyabbey Bay than in the south. This point is illustrated by a simple linear regression analysis of onlap altitude for seismic facies 2 to 5, plotted on north-south and east-west scales (fig. 5.27). The maximum change in gradient occurs parallel to a NW-SE axis, yielding values between 0.67 m/km and 2m/km; the lower limit is similar to gradients resulting from crustal flexure modelling (Lambeck, 1996). It is possible that this disparity in onlap heights reflects tilting during isostatic recovery. Greyabbey Bay may have been affected by crustal flexure caused by both the main Irish ice mass (NW of Strangford Lough) and the distant, more extensive Scottish ice mass. The NW-SE trend in late-glacial onlap altitudes from Greyabbey Bay suggests that the Irish ice mass exerted a stronger control in this area. The general slowing of recovery rates during the Holocene (Carter 1982) should be reflected by a concomitant decrease in vertical onlap contact height differences across the bay. This trend is not supported by the data (fig. 5.27), suggesting that whilst isostacy may have dictated the general trend in onlap contact heights, simple recovery alone is an insufficient mechanism. It appears that erosion on Unconformity B may be at least partially responsible for the pattern of onlap contacts within Greyabbey Bay.

It has been demonstrated that high-resolution marine seismology can detect sediment contact height variability on a scale related to ice-driven crustal warping, across short (several km) baselines. The standard approach to the determination of isostatic recovery rates requires correlation of numerous cores (e.g. Påsse, 1998). It is suggested that use of Chirp sub-bottom profiling in more sheltered environments might represent a rapid, inexpensive method of studying isostatically controlled sedimentation patterns, requiring fewer cores than are presently necessary.

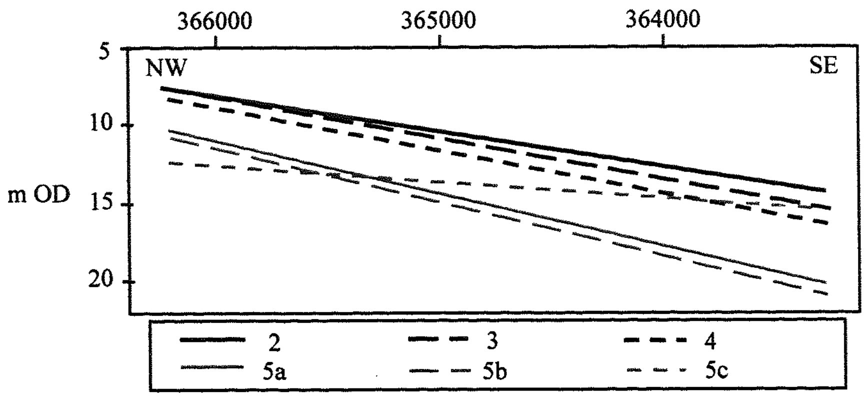

Fig. 5.27: Onlap contact heights for six late-glacial stratal surfaces in Greyabbey Bay. This distribution of contact heights suggests that tilt has affected facies 2 less than subsequent deposits 3 to 5b, the reverse of the result expected for simple isostatic recovery.

McCabe (1996, 1997) proposes early late-glacial deepwater conditions on the north-east coast. This is supported by AMS ^{14}C-derived, calibrated dates of c.16500 BP from Killard Point muds, inferred to have been deposited in 25m of water (McCabe *et al*, 1984). Marine muds at 0m OD on Rough Island have been (^{14}C) dated to 15246 ± 229 BP by McCabe (1996), who infers deep water conditions here at this time. At Roddans Port, two samples of non-marine biogenic material provide calibrated dates of 13787 ± 45 BP and 13269 ± 146 BP at -1.1 and -1.3m OD respectively (Devoy, 1983). These dates broadly support the concept of rapidly falling RSL between 15000 and 13000 BP, although the Rough Island muds may not correlate with deep-water deposits described from Killard Point. A detailed palynological study is necessary for improved constraint of the RSL curve at this time.

5.16: The Early Holocene RSL Minimum

Unconformity B is proposed as representing the transition from late-glacial falling RSL to recovery during the early Holocene. The nature of this unconformity has not yet been defined. 3D reconstructions of this surface in Greyabbey Bay suggest that an early Holocene sea level fall of 10-30 metres would have subaerially exposed large expanses of soft sediment for a period of several thousand years. No buried palaeo-channels relating to lowered base levels have been observed in the seismic dataset, but this is unsurprising, as the modern north eastern lough shore also exhibits only a small number of minor tributary streams. The maximum depth of erosion identifiable on unconformity B varies between 0 and -26m OD across the seismic dataset. Shallow values often arise where detail is obscured by shallow gas blanking.

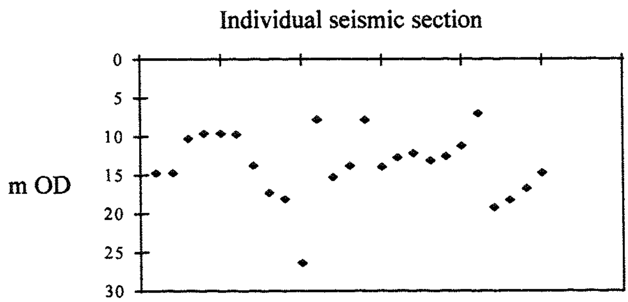

Fig. 5.28: Maximum depth of unconformity A visible on seismic sections throughout Strangford Lough. The maximum depth of erosion is -26m OD on line 3009; convergence of unconformities B and C on this line suggest that unconformity C has removed material beneath the original depth of unconformity B.

Erosion on unconformity B generally occurs above -20m OD. At four locations in the northern main channel, a pronounced bench has been cut into the exposed till at -17m OD to -20m OD (see fig. 4.7, p. 49). This feature may represent shoreface erosion during the early Holocene RSL minimum. The depth below sea level to which storm wave-induced erosion might have occurred is theoretically calculable (US Army, 1984), if the fetch, water depth and wind speed are satisfactorily estimated. These are obtained from present day bathymetry and the published wave characteristic curves of Draper (1980), to produce an approximate maximum wavelength thus:

$$L \approx (gT^2 / 2\pi) \sqrt{(\tanh \{(4d\pi^2) / (gT^2)\})}$$

Eqn. 5.2: A ±5% accurate calculation of wavelength for gravity waves induced by wind, from the Shore Protection Manual (US Army, 1984). This depth is assumed to be effectively half of the wavelength. L = wavelength (m), g = 9.81ms⁻² T = wave period (sec.), d = water depth (m).

The maximum present-day depth of wave-seabed interaction is calculated at -11m OD, assuming storm conditions (wind 45 knots, water depth 50m & uninterrupted fetch of 14km). This is a significant overestimate, as water depths reach 50m only in the most southerly basin of Strangford Lough and northern areas are protected by a wave-attenuating sill[9] at c. -11m OD. Large storm waves cannot have cut unconformity B, as reduction of sea level from the present value toward the sill height of -11m results in reduced fetch and a maximum interaction depth of 1m for waves generated beyond the sill.

The maximum depth of unconformity B and eroded bench features is approximately -20m OD. Carter (1982) suggested a likely RSL of -20 to -30m OD for the north eastern coast of Ireland. Cooper *et al* (1998) report similar features at -30m in Belfast Lough. The Narrows forms a sill between Strangford Lough and the Irish Sea, at -23m OD (Admiralty Chart 2156); current velocities across this sill exceed $4ms^{-1}$ during peak flow, creating a strongly erosive environment (Kirk *et al* 1990 & D.o.ENI sublittoral survey). The difference in erosion depths between Belfast and Strangford Loughs might be explained by three hypotheses:

(1) Similar RSL in both areas, but greater storm erosion in Belfast Lough, which is more exposed.

(2) Differential isostatic recovery rates.

(3) Different sea levels caused by RSL falling below the lip of Strangford Lough and isolating it from the Irish Sea.

Hypotheses (1) and (2) are quite possible, but investigation is beyond the scope of this project. Hypothesis (3) requires 3m of erosion in the Narrows since c.9500 BP (Carter, 1982) to bring the sill up to the maximum depth of erosion on unconformity B. This is possible, given the strength of the present tidal regime.

[9] Bathymetric data shows the sill to comprise discrete mounds south of Mahee Point, which are possibly submerged drumlins.

Unpublished groundwater investigations in Newtownards boreholes and resistivity transects across the mud flats of northern Strangford Lough (Kalin, pers. comm. 1999) indicate the presence of fresh water over 2000 years in age, deep within the sediment pile. It has been argued that this indicates freshwater lacustrine conditions and isolation from the Irish Sea.

It is very possible that Strangford Lough underwent a period of isolation from the Irish Sea during the early Holocene. Future coring is proposed for this area, using the seismic information presented in this chapter as a guide to the most effective areas. The proposed timing of this event possesses strong archaeological significance: the first humans are thought to have arrived on the north-east coast approximately 9000 years ago. A freshwater body of this magnitude would provide a major source of food and water and thus the lough might possess far greater archaeological potential than has previously been suspected. If freshwater deposits exist, they will be found at depths greater than -20m OD. No independent facies representing freshwater deposition can be identified in seismic section, although there are areas within the northern basin where horizons around Unconformity B become indistinguishable. Facies 7 is observed at c. -5m OD in Greyabbey Bay, suggesting that there may be deposits intermediate between facies 6 and 7 in areas of the lough which represented low energy lacustrine environments during the early Holocene and have since lain undisturbed. Inter-drumlin areas located in the unmapped south-west region of the lough may fulfil these criteria and contain sediments which provide evidence for lacustrine deposition.

5.17: The Holocene post-glacial RSL recovery

The post-glacial sediment record (units 3 & 4) appears simpler in Greyabbey Bay than the central and northern basins of Strangford Lough, where it is complicated by erosion on unconformities C and D. In Greyabbey Bay, facies 7 and 8 are interpreted as representing deposition of the Estuarine Clay as RSL recovered; up to 15m of Estuarine Clay deposits have been imaged in this area.

Seismic facies 7 and 8 greatly overstep the underlying deposits in a manner similar to that observed in Belfast Lough, where this is ascribed to rapid RSL rise (Quinn *et al*, 1999 & *pers. comm.*). Facies 8 is of far greater areal extent than facies

7, and may correspond to the mid-late Holocene RSL maximum. The Estuarine Clay is notable for its wide distribution of shallow gas, believed to be methane from buried organic material. Organic materials, including seaweed and wood, frequently occur within the Estuarine Clay on the Lecale Peninsula and the Newtownards boreholes. Gas is concentrated on the basin margins, which suggests a terrigenous or intertidal origin for the organic matter.

There is evidence for tidal erosion and deposition within the central and northern basins of Strangford Lough. In this area, facies 8 and 9 are truncated by unconformities C and D. Tidal currents in this area are far greater than in Greyabbey Bay (Kirk *et al*, 1990) and these unconformities are interpreted as representing tidal current erosion. The asymmetrical geometry of facies 9 is typical of deposits laid down on the flanks of tidal channels (Sysivitski & Shaw, 1995). Facies 7 and 8 do not exhibit this geometry, suggesting changes in the tidal regime during the middle to late Holocene. These changes produced shifting loci of erosion and deposition within the northern and central eastern lough, whilst in wave-dominated Greyabbey Bay (Kirk *et al* 1990, Ryan & Cooper 1998), the effect appears negligible. Seismic evidence from the central basin suggests that facies 7 and 8 were deposited when sea level was higher than -8m OD, prior to tidal erosion on unconformity C.

5.18: Evolution of Strangford Lough since the Midlandian glaciation

Published literature concerning sea level change in north-eastern Ireland proposes that late-glacial relative sea levels were higher than at present, during northwards ice retreat. Seismic surveying of Greyabbey Bay has discovered features resembling pockmarks; it has here been suggested that these were caused by submarine porewater escape, following local deglaciation. The true height of RSL during the early late-glacial (c. 16900 BP onward) is undetermined. Prominent notches at +12m, +14.6m and +16.8m OD on the Lecale and Ards peninsulas are covered by late-glacial marine muds, which provide a minimum value for the late-glacial RSL maximum. RSLs of +25m OD are inferred by McCabe (1996, 1997), who argues that the Killard Point muds show no signs of reworking, placing them below wavebase (c. 20m water depth). A dedicated palynological investigation of higher-level inter-drumlin hollows of the region might satisfactorily resolve the issue of water depths; coring within the lough can now be orientated toward suitable basins, which have been located by creation of 3D surface reconstructions. Late-glacial deposits exhibit a generally thin-bedded (<1m) concordant stratigraphy whose onlap patterns are compatible with falling RSL.

Comparison of seismic, borehole and AMS ^{14}C data suggests that around 14-13000 BP, RSL fell through 0m OD and continued decreasing to an early Holocene minimum of c. -20m OD. It is proposed that Strangford Lough may have been isolated from the Irish Sea during this RSL minimum. This has important archaeological implications, as the significance of the lough both as a food and water source and in terms of the wildlife attracted to it would probably change greatly if it was non-marine during the early Mesolithic settlement of Ireland. Further palynological investigation of properly targeted cores is required if the question of isolation is to be unequivocally solved.

The timing of RSL recovery in Strangford Lough is presently inadequately constrained. Several studies of Holocene sea level change in the area have been discussed in this chapter, but the RSL curve remains poorly constrained until the middle Holocene. During this recovery, the Estuarine Clay was deposited, to a recorded thickness of approximately 15-19m. Rising RSL appears to have been accompanied by shifts in the tidal regime, resulting in fluctuation between erosion and deposition throughout the lough.

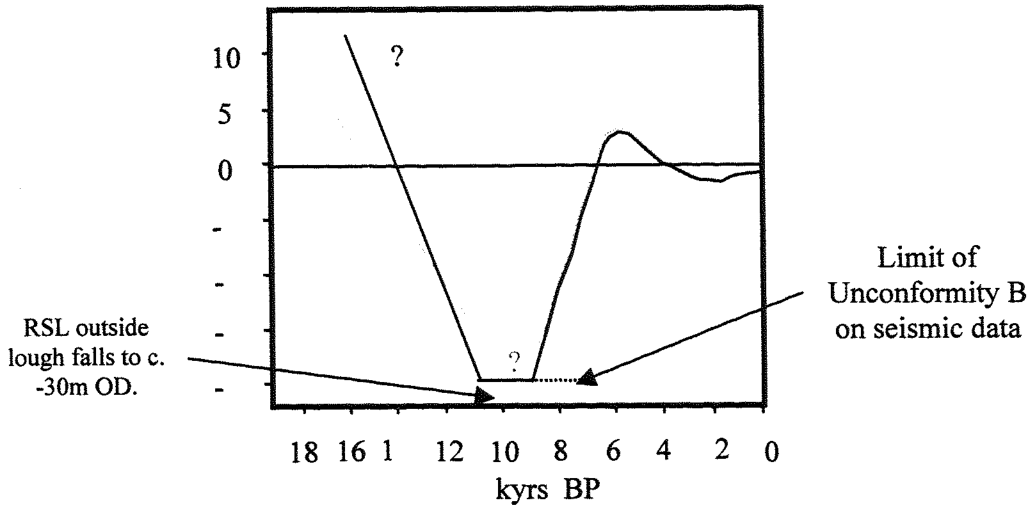

Fig. 5.29: RSL curves for Strangford Lough. Grey curve represents the general NE Ireland curve presented by Carter (1982)(red in fig. 5.1). Black curve relates specifically to the RSL curve for Strangford Lough, modified with respect to data discussed in this chapter.

Seismic data from Strangford Lough has yielded information upon sediment distribution and the evolution of local sedimentation. It is clear that this study requires additional palynological input, if the local history of relative sea level is to be accurately determined. Information from erosion surfaces observed in seismic section suggests that the RSL curve proposed by Carter should be amended both for Strangford Lough (fig. 5.29), and outside the lough, where data presented by Cooper *et al* (1998) suggests early Holocene RSL of -30m OD.

5.19: Conclusions

- A high-resolution seismic stratigraphy has been established from Chirp and Boomer data acquired in Strangford Lough. This stratigraphy exhibits general correlation with cores and field evidence from the surrounding shores. The earliest widespread deposit is a unit of marine mud, which unconformably drapes the underlying drumlinised till. The top of this unit is bounded by a second unconformity, which exhibits erosion at altitudes above -20m OD, and is identified with an early Holocene RSL minimum. Seismic stratigraphic contacts between facies within this unit may be interpreted as representing either an offlapping depositional sequence or an erosive surface; both interpretations support the general concept of falling RSL. Evidence from Belfast Lough supports the hypothesis that RSL fell up to 10m beneath base level in the Narrows during the early Holocene, with the result that Strangford Lough underwent isolation from the Irish Sea and lacustrine conditions prevailed. The unconformity representing low early Holocene RSL is overlain by up to 19m of Estuarine Clay deposits, which reflect rising sea levels and increased tidal circulation within the lough.

- Sedimentation rates in local basins during late- and post-glacial times have been estimated as 1.2mmyr^{-1}. The most well preserved sediments have been identified within Greyabbey Bay, where erosion during the early Holocene RSL minimum appears minimal. Modern tidal scouring of the central and northern basins is capable of eroding all sediment to the depth of the basal glacial till deposits.

Theme 2

The Application of High-Resolution Seismology as an Archaeological Reconnaissance and Mapping Tool in Extremely Shallow Water

Chapter 6: Inter-tidal zone surveying and coastal fish weirs

Overview

In this chapter, the potential archaeological value of physically inaccessible expanses of the inter-tidal zone is identified and the need for a fully inter-disciplinary investigative methodology proposed. The integration of side scan sonar within such a survey methodology is to be investigated within this Theme. Prior to discussion of supporting field data, potential targets for side scan survey are described. These targets are ancient fishing weirs, of wooden or stone construction, originally located within the inter-tidal zone during the period of operation, but frequently drowned during subsequent marine transgression. Investigation of these structures may yield important information upon the local economy and subsistence culture of coastal settlements.

6.1: Introduction

Between the domains of maritime and terrestrial archaeology is an area in which the approaches to survey and recording adopted by neither discipline are entirely suited, nor can be easily and consistently applied (fig. 6.1). This area is delimited by the Mean High and Low Water Spring Tide isobaths (the inter-tidal zone), but in practical terms, often extends into slightly deeper water (shallow sub-tidal zone). The effectiveness and viability of a terrestrial archaeological approach diminishes with the increased physical extent of the exposed inter-tidal area to be surveyed, as narrow tidal windows and dangerously soft mud banks preclude detailed reconnaissance by field walking (Fulford *et al*, 1997). Good visibility and slack water are generally necessary for the adoption of a safe and effective maritime approach to large sites, yet in many shallow coastal regions, neither can be predicted with any confidence. Coastal environments comprising large expanses of soft, easily mobilised, tidally exposed sediment - such as the Greater Thames estuary - are unsuited to traditionally effective traditional archaeological approaches and thus require investigation and mapping by alternative means. There is also a growing need for the capability to conduct rapid and effective archaeological investigations within this area, resulting from the increasing stress exerted by coastal developers and rising sea levels (Dix & Bull 1996, Draper-Ali 1998).

Figure 6.1 demonstrates the overlap between survey techniques employed by archaeologists. Every site presents a different environment and a unique archaeological problem, so the approach must be tailored to suit the tidal regime and weather conditions.

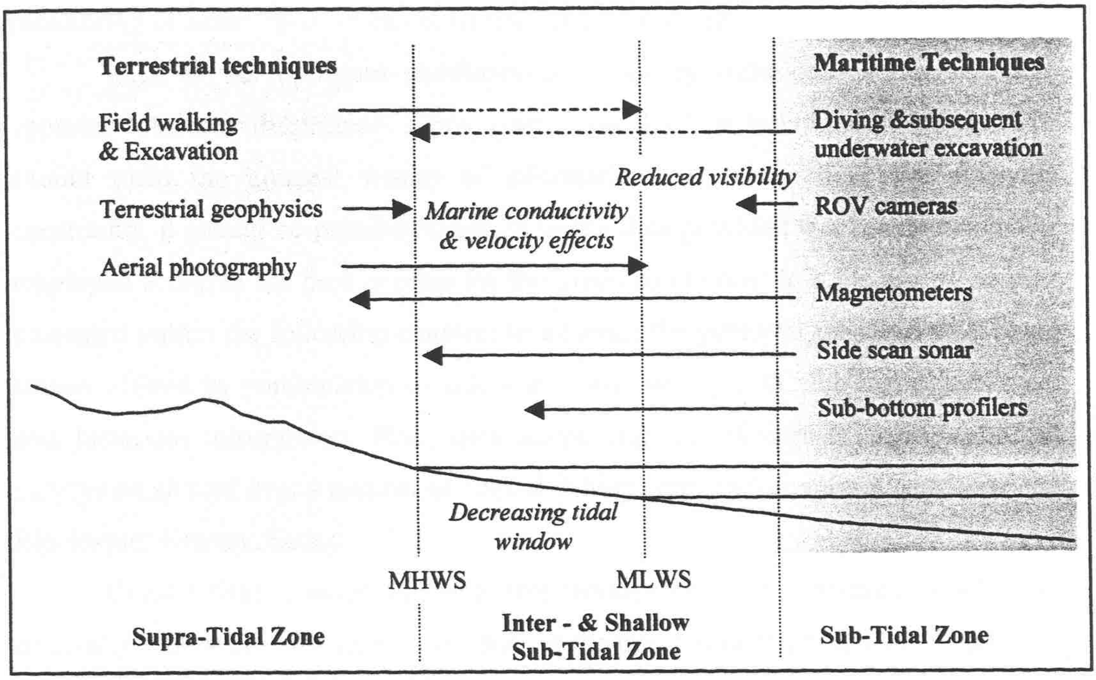

Fig. 6.1: Overlap in applicability of terrestrial and maritime survey techniques within the inter- and shallow sub-tidal zone.

Magnetometry and side scan sonar are rapid, non-penetrative techniques commonly used for archaeological survey within the subtidal zone[1], which offer potential for use as reconnaissance and mapping tools within the inter-tidal zone. A substantial amount of evidence for human activity within the inter-tidal zone (e.g. wooden jetties, early boats and fishing weirs) comprises wooden structures lacking strongly magnetised content, and cannot be located or mapped by magnetometry. It is also impossible to distinguish the signature of archaeologically significant targets from noise of modern anthropogenic origin. Acoustic mapping techniques facilitate

[1] A third technique with great potential is *swath bathymetry*, an acoustic survey device producing extremely accurate plots of seabed topography. Unlike side scan sonar, this method does not yield information upon the relative texture of the seabed, and can miss small upstanding targets. Future generations of integrated survey device are likely to feature combinations of all three devices, to great effect (and cost).

seamless mapping of palaeosurfaces between terrestrial and marine environments, enhancing knowledge of site context. Recent work by Quinn *et al.* (1997) presented theoretical and empirical hypotheses concerning the significant acoustic reflectivity of degraded wood within the shallow marine environment. Combined Chirp and side scan sonar mapping of the Invincible wreck site (Quinn *et al*, 1998a) subsequently demonstrated the potential for high-resolution marine seismic mapping and monitoring of submerged wrecks in hazardous environments.

What is the optimum combination of survey techniques for a seamless approach? An inter-disciplinary survey employing all of the techniques detailed above should yield the greatest wealth of information, but given time and financial constraints, it should be possible to obtain useful data provided that the methodology employed achieves the best overlap for the given conditions. It is the aim of studies presented within the following chapters to examine the potential for seamless coastal survey offered by combination of side scan sonar survey data with aerial, terrestrial and historical information. Field data supporting this discussion is drawn from surveys conducted over a number of coastal fishing weirs in Strangford Lough and the Blackwater Estuary, Essex.

Coastal fishing weirs[2] are extensive wooden or stone structures, which were originally built within the inter-tidal zone for the purpose of trapping fish. Weirs form an important element of the maritime landscape, as their presence provides important information upon the local economy and lifestyle, from Pre-historic time onward (e.g. Pederson *et al.*, 1997). Inundation by post-glacial sea level rise has drowned many British and Irish examples of this monument class, or placed them within dangerous, poorly accessible environments. The weirs of the Blackwater Estuary, for example, are located upon large expanses of dangerously soft mud, distant from shore and only rarely exposed, precluding extensive field investigation (Wallis 1993, Hall 1997). These weirs may be particularly important, as they have been ^{14}C dated to Saxon times and thus suggest that the local inter-tidal zone may represent an important resource of information on the poorly chronicled Early Medieval period in Essex.

To understand the significance to subsistence or trade represented by these structures, a safe, rapid, accurate and accurate means of mapping within the inter-tidal and shallow sub-tidal zones is required. Efficient and effective survey design requires careful consideration of the survey environment and probable target characteristics, therefore it is necessary to consider the conditions, structures and industry associated with stationary fishing, prior to discussing the surveys themselves (Chapter 7).

6.2: Coastal Fish Weirs

Fishing of rivers and the inter-tidal zone by use of stationary weirs is one of the oldest human food-gathering practices, although currently only rarely employed in the developed world (Lethbridge 1952, Salisbury 1991, Fischer 1995). The concerns of this study are specifically *coastal* fish weirs, which have been identified in several regions of Britain and Ireland and are classed under a Single Monument Class of the Monuments Protection Programme (RCHME, 1989), defined thus:

"A coastal fish weir comprises two artificial walls of stone and/or wood to which are attached nets and/or a trap to catch fish. The weir is located in coastal waters, either on a gently shelving coastline or in a river estuary. The walls are between 100m and 200m in length and form a substantial enclosure with a V- or L-shaped plan. The narrow point is on the seaward side."

The MPP definition does not fully encompass the scale of findings of recent years; some recently discovered weirs attain lengths of 2-12km (Dare 1994, Bannerman & Jones 1999). Wall height was commensurate with tidal range, building style and distance from shore; stone trap remnants in the Menai Strait indicate heights of 3 metres (Jones, 1983), whilst historical records from Essex suggest wooden weirs projecting approximately 2m above the seabed (Crump & Wallis, 1992). Spring tidal ranges in these areas are c. 7m and 5m respectively, suggesting that weirs were constructed for operation on a wide range of tides. Basic wooden weirs were constructed by driving stakes vertically into the sediment and joining them with wattle panelling woven from pliable lengths of wood and twigs (Fig. 6.2, 6.3). A second style of wooden trap was that known as the Essex *kiddle*, where the timber uprights were linked by netting rather than wattle.

[2] The term "weir" is derivative of the Anglo-Saxon word "*were*", meaning, "a stationary structure used for catching fish" (Strachan, 1997).

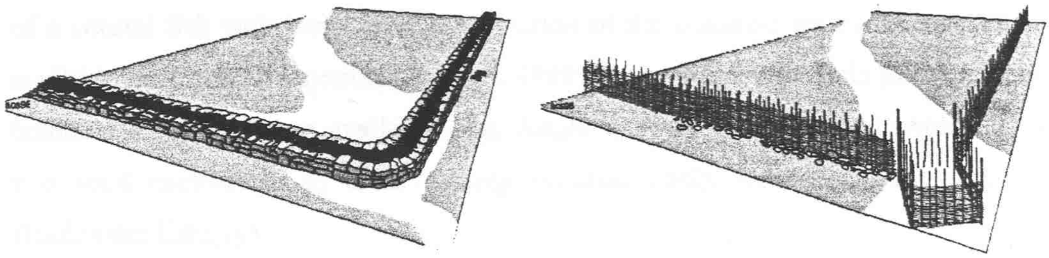

Fig. 6.2: Examples of stone (left) and wooden coastal fish weirs corresponding to the MPP definition. These examples are reconstructions of medieval fish weirs made by Aidan O'Sullivan, based on work in Strangford Lough (O'Sullivan et al. 1997).

The mechanics of weir operation were often dependent upon tidal flow direction; in Strangford Lough for example, fish follow the shoreline as the tide falls, so traps are appropriately oriented against their swim direction (McErlean, *pers. comm.*). At other locations, suggested weir geometries are extremely complex (e.g. Collins Creek: Strachan 1997, Hall & Clarke *in press*) and the exact mechanism of operation is difficult to envisage beyond the simple premise that the sites drained during low tide to facilitate fish extraction and trap repair. Weirs whose remnants suggest a complex structure may be the result of adaptive rebuilding in response to changes in sea level and local tidal circulation.

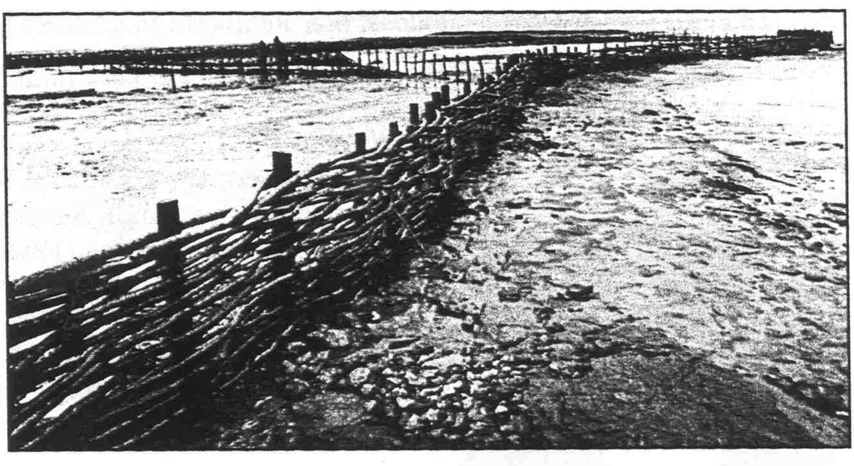

Fig. 6.3: Contemporary fish weir, exposed at low tide in the Severn Estuary (from Salisbury, 1991). This photograph demonstrates the use of upright wattling to divert fish into the trap closure, which is visible at the top right of the picture.

Fishing weirs are generally absent from high-energy coasts with narrow, rocky shorelines (Fulford *et al.*, 1997), where construction and maintenance would have rendered the technique hazardous and inefficient. The design and constituent elements of a coastal fish weir were usually a function of the coastline geometry and locally available materials (Bannerman & Jones, 1999). Stone weirs were built in areas where boulders or blocks were available (e.g. Anglesey, Strangford Lough); whilst wood was used exclusively in areas lacking suitable, easily workable stone (e.g. the Blackwater Estuary).

The total number of weirs in England is estimated at 400-500 (RCHME, 1989): the greatest recorded cluster consists of some 50 weirs identified on the West Somerset coast (e.g., McDonnell 1994, Nayling & Caseldine 1997, Rippon 1997, Hooke 1998, Hildich 1998, Riley 1999). Significant numbers of coastal weirs (fig. 6.4) have also been identified in Essex (Wilkinson & Murphy 1995, Hall & Clarke *in press*), North Wales (Jones, 1982), Northern Ireland (O'Sullivan *et al.* 1997), Scotland (Lethbridge, 1952) and North Munster, Ireland (O' Sullivan, 1994), plus lesser groups at other locations. The majority of these sites are Medieval or later in origin (Rippon, *pers. comm.*), but weirs dating to Saxon times have been discovered in the estuaries of the Rivers Blackwater (Strachan, 1997) and Severn (Rippon, 1997). Proposed prehistoric fishing structures have been tentatively identified in the Stumble (Blackwater Estuary) (Wilkinson & Murphy, 1995), Severn (Nayling & Caseldine, 1997) and Wootton Creek (Isle of Wight Council, 1997). Given the Northern European origin of the Anglo-Saxon migration, it is perhaps significant that a large recorded resource of Mesolithic and Neolithic coastal fishing weirs has recently been reported from Denmark (Pederson *et al.*, 1997).

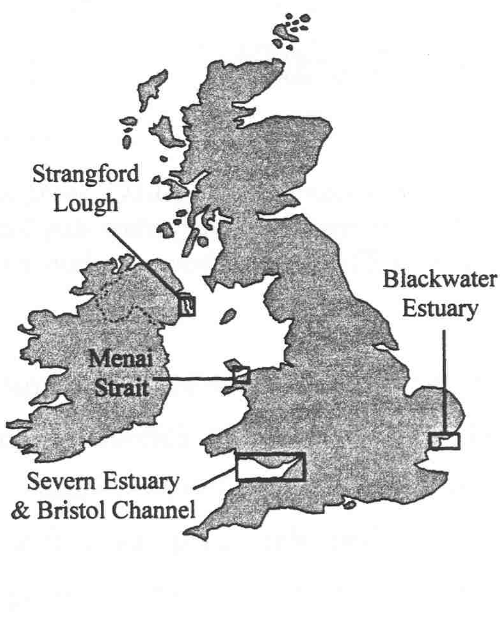

Fig. 6.4: Location of sites discussed in this chapter. Additional weir clusters occur within the Irish Shannon Estuary, the Solent, Scottish weirs, Kent, Cardigan Bay, Humberside, and Sussex, plus a number of other locations which appear to have lower concentrations of fisheries.

6.3: Construction and Operation of Static Fisheries

All coastal weirs are thought to have relied upon the water motion associated with a meso- to macro-scale tidal variation (RCHME, 1989) to entrap fish. The weir was located on the foreshore, such that it drained completely during the lowest state of any tide. Fish approaching the shore to feed upon a rising tide, would be carried behind the walls and trapped in a large enclosed area as the tide turned. Ebb tidal currents would then force the catch into nets and / or woven wicker traps at gaps in the walls, facilitating extraction by fishery workers. Other suggested fishing practices such as flood-tide capture (Blackwater estuary, Bruce, 1993) and the practice of fishing from boats in eddies created behind weir-like structures (Severn Estuary, Seebohm, 1913) are less well understood. Contemporary coastal fish weirs (Fig. 6.3, 6.5) such as those of the Severn Estuary (Salisbury, 1991) and an Essex kiddle constructed at Foulness in 1975 (Crump & Wallis, 1992), demonstrate the success of this practice. These recent structures, historical records and photography have facilitated artistic reconstruction of the appearance of static fisheries during Saxon and Medieval times (fig. 6.5).

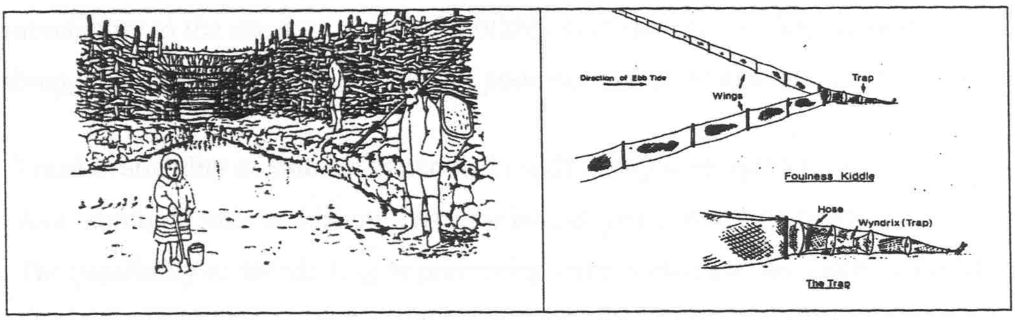

Fig. 6.5: Left - Photography and records from 1910 allow reconstruction of the operational state of a North Wales coastal fish weir (from Bannerman & Jones, 1999). Right - An Essex kiddle constructed and operated during 1975 (Crump & Wallis, 1992).

Construction and maintenance of a large static fishery would require continual labour, therefore this industry is likely to have formed a major part of the local economy in areas where static fishing was extensively practiced. A diverse range of species was caught in this manner, including flounders, plaice, sole, brill, dabs, sting ray, thornback ray, salmon (sea trout), garfish, gurnard, mullet, bass, shad and cuttlefish. The volume of fish captured was sometimes considerable: records indicate that the great weir of Gorad Rhos Fynach (N Wales) once captured 35 000 herring on a single tide (Bannerman & Jones, 1999). Trap maintenance and catch removal during low tide required reliable links with the shore. Where this required the use of horse-drawn carts, access trackways were sometimes constructed across mudflats to service the weirs (Crump & Wallis, 1992). These trackways were constructed from similar materials as the weirs; large sections of this wattling have been recovered from sites around the Blackwater (Groves 1993, Hall 1997, Hall & Clarke *in press*) and also from similar sites in the UK (e.g. Hildich, 1998) and Denmark (Pederson *et al.*, 1997). The Domesday Book describes horse pastures on the Essex coast, kept solely for the purpose of fishery maintenance (Crump & Wallis, 1992).

Evidence from the prehistoric Danish fisheries sites near Halsskov (Pederson *et al.*, 1997) suggests that Neolithic Man lived close to his weirs, operating them during the Summer and Autumn months and removing the hurdling for repair during the Winter. Management of the fishery and coppicing of large expanses of local woodland would require greater organisational skills than generally credited to society at this time. Studies of eel bones retrieved from this area suggest that excessive catches were made and distributed or preserved for later consumption, ideas contradictory to the standard view of Neolithic subsistence. Four key requirements for fishing with stationary weirs in a time of poor external communication are outlined:

1. Local availability of suitable materials in sufficiently large quantities.
2. Availability of time and labour force for investment in weir construction.
3. The possibility of distributing or preserving large portions of the catch, which could not be immediately consumed by the fishery workers and their families.
4. Possession of a right to be at the fishery site and to harvest the catch.

In addition to the physical factors which determined the suitability of a coastal site for stationary fishing techniques (beach profile, material availability etc), it is thought that strong social and religious controls existed. There is a proven connection between the location of many fish weirs and monastic sites within the British Isles (Momber 1991, Fulford *et al.* 1997, O'Sullivan *et al.* 1997, Bannerman & Jones 1999), which may to some degree have been driven by periodic abstinence from meat, demanded by ecclesiastical regulations. It has been suggested that the fisheries of

Mersea Island and Bradwell, on the Blackwater, were owned and operated by local monasteries (Fulford *et al.*, 1997), although Hall & Clarke (*in press*) stress the lack of reliable evidence to support this suggestion. Fisheries in Greyabbey Bay, Strangford Lough, have also been attributed at least in part to Cistercian monastic activities (Williams, 1996).

6.4: Identification and Classification

Fish weirs are relatively simple to identify in the field, provided that they can initially be located (RCHME, 1989). Stone weirs are those most easily identified, as erosion usually consists of in-situ collapse of the original walls into linear associations of boulders upon the foreshore (fig. 6.6). It is however, possible to mistake lines of kelp-festooned boulders piled by breakers at the low tide mark, for stone-built weirs (Bannerman & Jones, 1999). The remnants of wooden weirs are often harder to identify, as some have been eroded to the level of the seabed and subsequently covered by mobile sediment (O'Sullivan *et al.* 1997). The geometry of stone weirs is easily described, as their remnants tend to comprise of readily identified individual linear features. It is likely that rebuilding after winter storms consisted of simply replacing dislodged stones on these single-limb structures. In contrast, many wooden weirs appear to comprise multiple limbs, sub-parallel and obliquely crossing multiple walls and unexplained offshoots. It is likely that these vast arrays of uprights represent several hundred years of stationary fishing, during which the weir would have been rebuilt and repaired many times in response to storms, changing sea level, sediment transport and wood degradation. Old posts would simply have been left to rot in-situ, producing the confusing patterns visible today (fig 6.6). At Collins Creek, samples taken from upstanding remnants of wooden weirs indicate that most stakes at this site were cut from oak (Groves, 1993), whilst a trap discovered lying completely below the sediment in Greyabbey Bay comprised of hazel, ash and oak stakes (Williams, 1996). These stumps were extremely soft and degraded; the type of wood used in construction may be an important element in assessing the preservation potential of ancient wooden weirs.

Figure 6.6: Top - Remains of a medieval stone fish weir in Greyabbey Bay, Strangford Lough (left) and a Saxon / Medieval wooden weir complex on the Nass, Blackwater Estuary (right). The apparently complex structure suggested by these wooden stumps may be a result of rebuilding over long periods of time. (Photographs: left - author & right - Strachan.) Bottom: Trap complexity as a result of rebuilding is clearly displayed in this aerial photograph of wooden structures in Whitstable Bay, Kent (RCHME).

Classification of coastal fishing weirs by purpose, date or even structural content is difficult, as weirs were often long-standing structures operated and modified by many successive parties. Stone weirs rarely contain unequivocally in-situ datable material, hence they are dated only from historical records and contemporaneous finds, whilst carbon dating of wooden weirs often yields a wide range of dates, which may only correspond to a portion of the weir's true period of usage. Bannerman & Jones (1999) propose a simple classification based on shape, assuming nothing beyond the archaeologist's ability to relate the relict form to that of the original operational structure (fig. 6.7). The purpose of this scheme is to facilitate comparison of weirs from different regions; the viability of this scheme and the significance of the results of any such comparison are examined in the following chapter.

Type	Description	Type	Description
1	*Natural features adopted as trap*	*5*	*Rectilinear*
2	*Semi-permanent wattle and wood*	*6*	*The "Vee" or "Double Vee" shaped trap*
3	*Modified natural feature trap*	*7*	*The "S" shaped weir*
4	*The crescent shaped trap*		

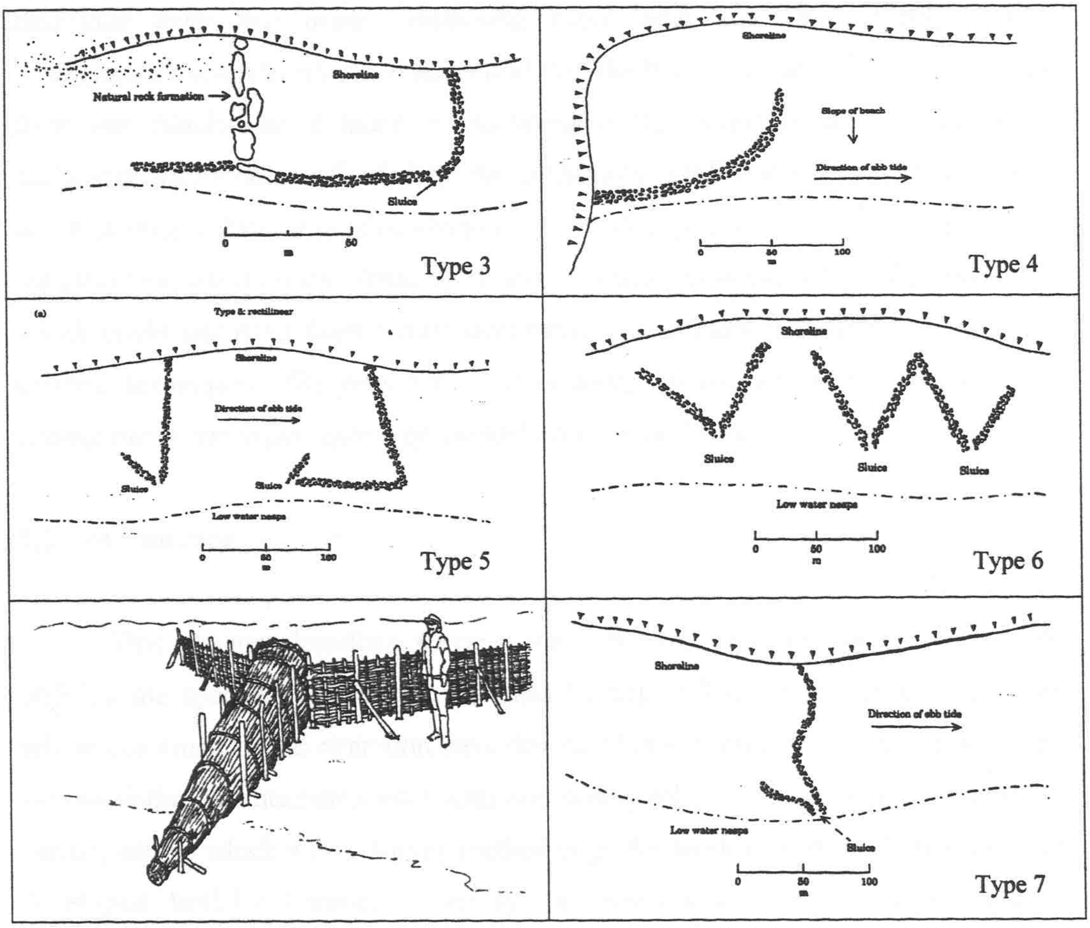

Fig. 6.7: Fish weir classification suggested by Bannerman & Jones, 1999 and examples of structures placed within this scheme. Top: the shape-based classification scheme. Top row: left - type 3 modified natural feature trap & right - type 4 crescent. Central row: left - type 5 rectilinear trap & right - type 6 "vee" and "double vee" traps. Bottom row: left: reconstruction of a simple "vee" & right - a type 7 "S" shape. All figures reproduced from Bannerman & Jones, 1999.

Chapter 7: Mapping Ancient Coastal Fish Weirs

Overview

This chapter is concerned with the application of high frequency side scan sonar to the problems of mapping ancient coastal fish weirs within the inter-tidal and shallow sub-tidal zones. Successful inter-tidal survey requires a co-ordinated inter-disciplinary approach; the methodology developed during this investigation is described and justified with reference to specific field examples. Surveys are described from two areas containing large inter-tidal archaeological sites: Strangford Lough (Northern Ireland) and the Blackwater Estuary (Essex, UK). Data from the Blackwater Estuary is particularly significant in demonstrating the additional information afforded by the integrated application of side scan sonar, aerial photography and field investigation. This data provides new information upon the structure, location and limits of several wooden fish-weirs of middle Saxon Age which could not have been easily, accurately and rapidly provided by alternative existing techniques. The implication of ongoing discoveries in this estuary may change the common perception of Anglo-Saxon life in Essex.

7.1: Introduction

This chapter describes surveys conducted over ancient coastal fish weirs, utilising the specially constructed combined Chirp and side scan survey catamaran whose construction and operation were described in section 2.7. The inclusion of this system within an integrated inter-tidal archaeological survey required a field-testing period, during which a new survey methodology for work in very shallow water was developed. Initial calibration of the system over known inter-tidal archaeological targets was conducted in Strangford Lough, a sheltered marine inlet on the Northeast coast of Ireland (fig. 7.1 & chapter 4 & 5, this volume). The lough contains a number of stone fish traps dated to between the 8th and 19th centuries AD (McErlean *in progress*, O'Sullivan *et al* 1997), which are located close to shore and accessible at low tide. These sites had previously been comprehensively photographed and investigated by field archaeologists (McErlean, *in progress*), so the site was ideal for the comparison of side scan images, field data and photography. Sea level in

Strangford Lough has remained above OD since c. 6000 BP[1] (4000 BC) (fig. 7.2)(Carter 1982, Chapter 5), hence it was expected that any weirs dating from within the last six millennia should lie within the modern inter-tidal zone. This suggested that it should be possible to ground-truth geophysical data by reference to the preceding field and aerial investigations. Thus Strangford Lough provided an ideal testing ground for calibration and investigation into the applications of high-resolution side scan sonar within the shallow waters of the inter-tidal environment.

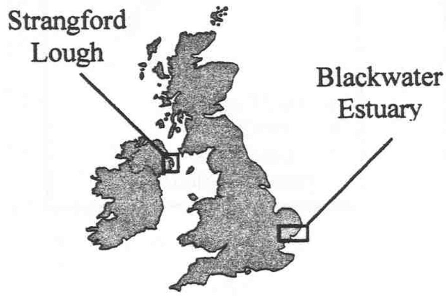

Fig. 7.1: Location of survey areas described in this chapter. Initial testing of the survey catamaran was conducted over previously documented Medieval stone fishing weirs in Strangford Lough, Northern Ireland. Success at this site was followed by a second survey season in the Blackwater Estuary, Essex. In the Blackwater estuary, the targets were the often permanently submerged remains of wooden fishing structures dating to Saxon times.

Subsequent to the establishment of a basic methodology, inter-tidal side scan survey was implemented within the reconnaissance and mapping of a more complex environment: the Blackwater Estuary of Essex (Fig. 7.1). This estuary contains a number of important inter-tidal sites including the well documented areas of The Stumble (Fulford *et al.* 1997) and The Collins (Dare 1994, Hall & Clarke *in press*).

The Essex coast has undergone gradual (although oscillatory) transgression and erosion of the inter-tidal and near-shore coastal landscape throughout the Holocene, at an approximate rate of $1 mmyr^{-1}$. (Shennan, 1987). The resultant increase in tidal and wave energy within the estuary has led to recent rapid destruction of structures on exposed sites such as Collins Creek, where the estimated rate of erosion is $10 cmyr^{-1}$. (Hall *pers. comm.* Wilkinson & Murphy 1986, 1995). Recognition of the probable importance of the Blackwater Estuary inter-tidal zone was made by Wilkinson *et al* (1988), in observing that:

[1] Dating systems vary between authors and disciplines. In order maintain a degree of consistency, the originally published format of any date is cited, with the corresponding alternative in brackets.

"The main environmental factor influencing the location, type and distribution of archaeological sites in the estuarine region of Essex appears to have been the position of the High Water Mark and its change through time."

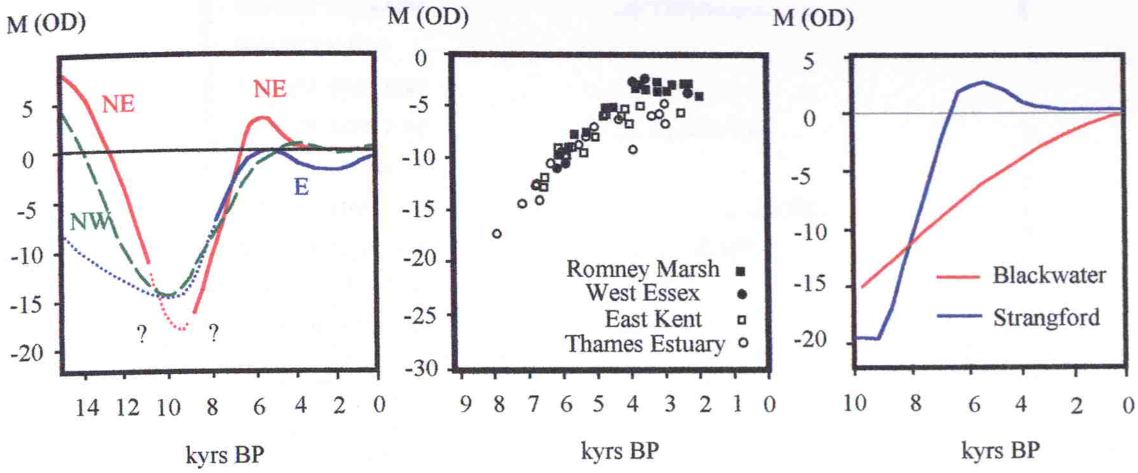

Fig. 7.2: Published regional Relative Sea Level curves for Northern Ireland (left), data for South-east England (centre) and curves for the specific localities of Strangford Lough and the Blackwater Estuary (right). All heights are relative to OD (Newlyn) which is c. 0.4m below OD (Belfast). Times are given in kyrs BP for consistency with Chapter 5 and standard sea level literature. Sources: left - Carter 1982, 1987 & Carter et al., 1989, centre - Long & Roberts (1997), right - Wilkinson & Murphy (1995)(Essex) and modified Carter curve (see chapter 5).

In addition to the better documented sites, a number of large wooden fish weir complexes were identified during the early 1990's (Bruce 1993, Crump & Wallis 1992, Dare 1994, Wilkinson & Murphy 1995); these are only occasionally tidally exposed and lie largely inaccessible on mudflats at the estuary mouth. Significantly, some of these sites appear to extend below MLWS and their true extent cannot be established from aerial photography or by field inspection. ^{14}C dating of stakes removed from these sites provided dates comparable with Saxon times (Strachan 1997, Hall & Clarke *in press*) (fig. 7.3). This date, coupled with the apparent sub-tidal extent of the structures, implies that many further sites may now lie a metre or more below MLWS. The true age of the structures may be somewhat greater, as the dating record is insufficient for estimation of chronological trends in weir construction.

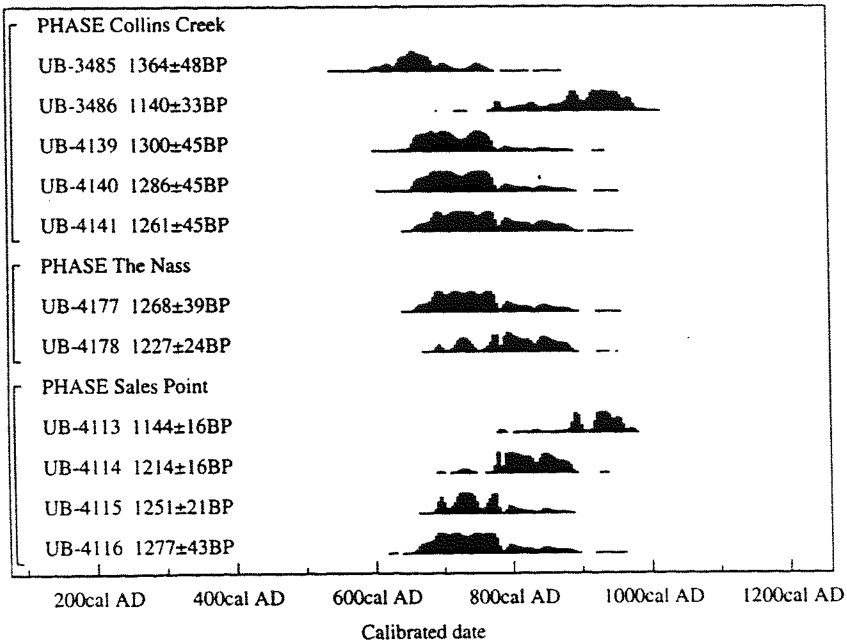

Fig. 7.3: Calibrated ^{14}C dates from wooden fish weir components extracted from three sites in the Blackwater estuary, Essex. Reproduced from Hall & Clarke (in press). These dates are strongly suggestive of repetitive site use during the Anglo-Saxon period.

In summary, Strangford Lough and the Blackwater Estuary provided two contrasting survey environments and objectives. In Northern Ireland, work focussed upon calibration of the side scan sonar catamaran over known inter-tidal targets and on investigation of the evolution of the submerged physical landscape; this chapter is concerned only with the calibration exercise. In Essex, the potential for imaging ancient wooden structures within the inter- and shallow sub-tidal zones was investigated in greater detail, and landscape variability was considered only in the context of the direct relationship between fishing structures and the sediments in which they were originally embedded.

This chapter has been structured such that initial calibration work in Strangford Lough precedes discussion of more exploration-orientated surveys in the Blackwater Estuary.

7.2: An introduction to the stone fish weirs of Strangford Lough

The physical characteristics of Strangford Lough have been described previously (Chapters 3, 4 & 5), with respect to the sedimentary evolution and sea level history of the region. The main purpose of this archaeological element within the Strangford Lough survey was calibration of the side scan system against a set of known archaeological targets, as described above. The sites chosen, close to Greyabbey in the north-east of the lough, contained at least 16 wooden and stone fish weirs, which had previously been investigated by the Coastal Research Unit (Williams 1996, O'Sullivan *et al.* 1997, McErlean *in progress*). These weirs have been dated between the C8th and C13th. What follows is a short description of the human history of the region around the shores of Strangford Lough.

Colonisation of Ireland from mainland Britain is believed to have begun in the early Mesolithic, c. 7000 BC (9000 BP) (McAuley, 1996). The route followed by the earliest settlers is controversial; the presence of a land bridge across the Malin Sea is thought to be highly improbable (Cooper *et al*, 1998). In Chapter 5 it was suggested that Strangford Lough underwent gradual transition from freshwater lacustrine to marine conditions during the early Holocene (9500 BP (c. 7500 BC)). This alters the common perception that Strangford Lough offered sheltered marine access to the interior during the early Mesolithic (e.g. ASCD, 1966). Marine transgression throughout the Mesolithic created a gradually expanding exploitable area of wetlands and open water. Evidence for Mesolithic and Neolithic activity on the shores of Strangford Lough is provided by flint implements retrieved from Littorina (raised beach) deposits (Movius, 1940). The majority of recorded Mesolithic sites lie amongst the sheltered islands and embayments of the north-west coast of the lough (ASCD, 1966). The early Holocene transgression which created Strangford Lough in its present form, has also potentially drowned and buried much of the evidence for early human activity (ASCD, 1966).

At the base of the inter-tidal zone in Greyabbey Bay (GR 3572 3667), preserved trees dating to c.8000 BP (6000 BC) provide evidence of deforestation since the early Holocene (Williams, 1996). The Mesolithic landscape was densely forested, thus the most inviting areas for habitation at this time were likely to be the coast and lakeshores, where important food resources could be exploited. The rich diversity of birds and fish associated with Strangford Lough were an attraction to the area, as evidenced by the discovery of Mesolithic tools and middens containing the bones of marine fish species, on the shores of islands within the lough (ASCD 1966, Woodman 1978, McAuley 1996). The region around Strangford Lough would have provided freshwater fish, land mammals, sea fish, oysters, sea mammals and an abundance of exploitable wildfowl, such as geese. It has been suggested that settlement of County Down during the Early and Later Mesolithic was probably nomadic, with the availability of food dictating seasonal migrations between regions (Woodman 1978, Mallory & Hartwell 1997).

A further phase of migration from Britain marked the onset of the Neolithic in Ireland, with the introduction of farming and stock-rearing settlements around 4000 BC (6000 BP) (ASCD 1966, Mallory & Hartwell 1997). The first permanent structures in Co. Down appeared during the Neolithic. These structures were isolated farmsteads, of plan dimensions as great as 6m by 15m. Evidence for human activities in Co. Down during the Neolithic, Bronze Age and Iron Age is very limited. It is thought that in Down, forest clearance during the Neolithic was less extensive than elsewhere in Ireland. There is a small amount of evidence suggesting that cereal crops were grown, whilst the bones of ox, sheep of goat, pig and dog indicate the type of stock-rearing undertaken (ASCD 1966). A paucity of deer bones in the Neolithic levels suggests that hunting was a lesser activity, despite finds of Neolithic arrowheads. At this stage, sea level was at approximately the same level as present, if not higher (Carter 1982 & Chapter 5).

Bronze Age pottery has been recovered from isolated sites on the east shore of Strangford Lough and a large settlement has been discovered to the south, at Downpatrick (ASCD, 1966). Further evidence for Bronze Age activity in the area of interest (north-east Strangford Lough) is rare, until the arrival of the Early Christians during the 5th Century AD. The most common structure remaining from the Early Historic (C5th-12th) period in County Down is the rath - a small, fortified enclosure often surrounded by a wall and ditch. Several raths are recorded to the north of Greyabbey Bay and one is located close to the shore in the survey area of Greyabbey Bay (Williams, 1996). There is a significant coastal resource dating from this period, which suggests substantial exploitation of the marine resource.

Evidence representing organised exploitation of the inter-tidal zone appears in the C8th, in the form of wooden fish weirs in Greyabbey Bay (Williams 1996, O'Sullivan *et al* 1997, McErlean *in progress*) and a series of well preserved tidal mills dating to 619-787 AD (1331-1163 BP) recently discovered at Nendrum (McErlean, *in progress*). An Early Christian church and associated earthworks have been found on Chapel Island (GR 3554 3672), close to a large wooden fish weir dated to 711-889 AD (1061-1239 BP). There were a number of major monastic sites around the lough, one of the most important of which was at Nendrum (GR 3525 3638) c. 639 AD (1311 BP) (Hamlin, 1997); it is possible that the church on Chapel Island represents a satellite of the main mission (O'Sullivan *et al*, 1997). Stone-built fish weirs are located to the east and west of the chapel site and it is possible that these may also have been constructed and maintained by the inhabitants of the island. The timing of the island's abandonment is unknown, however, and these stone traps could relate to the later presence of the Cistercians at Greyabbey.

Although the Vikings provided the lough with its name (Strangfjord), they left little evidence of their passage through the region. The first Vikings arrived in 795 AD (1155 BP), and returned repeatedly for over 200 years, initially to raid coastal settlements and later to settle and establish trade links. It is thought that a small trading port was established at the mouth of Strangford Lough (ASCD, 1966). There is documentary evidence for the presence of a Viking fleet upon the lough during the middle of the tenth century AD, although very few finds have been made during excavations at Nendrum (Hamlin, 1997).

John de Courcy led the Norman invasion of east Down in 1177; the subsequent Anglo-Norman occupation greatly altered the structure of society around Strangford Lough, founding numerous manors on the lough shore, some protected by fortified mottes (McAuley 1996). They rapidly re-organised the use of the land around the lough and introduced the Cistercian religion to Down, founding an abbey on the shores at Grey in 1193. A large number of wooden-built fish weirs have been discovered in this area, supplying ^{14}C dates of 1023-1161 AD / 1250-1273 AD (c. 858 & 689 BP), 1037-1188 AD (838 BP) and 1046-1218 AD (818 BP) (O'Sullivan *et al.*, 1997). It is thought that the Cistercians were determinedly self-sufficient and the construction of the monastery by an already large local community would have led to intensification of fishing activities and the construction of stone weirs. The total duration of fishing at Greyabbey is uncertain; late C16th maps of eastern Ulster indicate the presence of "fisheries of all kinds" at Greyabbey, but by 1683 the practice of fishing by stationary coastal structures had died out (O'Sullivan *et al*, 1997).

7.3 Discovery and Investigation of the Strangford Lough Fishing Weirs

The sea level history of Strangford Lough indicates that the inter-tidal zone is unlikely to have extended to seaward of its present limits for approximately 6000 years, although it may have transgressed some distance further inland. Consequently, the shallow inter-tidal zone contains a concentration of many important and chronologically diverse structures, including fish weirs, jetties, occupation sites, piers, saltworks, slipways and artificial channels. A detailed investigation of the inter-tidal zone conducted between 1995 and 1999 yielded diverse and important finds in widespread locations (Williams 1996, O'Sullivan *et al.* 1997, McErlean *in progress,*). This survey made use of complete vertical aerial photographic coverage and detailed field inspection, followed by excavation and protection where applicable.

Strangford Lough contains both wooden and stone fish weirs, the largest concentration of which occur in the Greyabbey Bay and Chapel Island areas, in the Northeast of the lough (fig. 7.3). The wooden weirs do not appear on the vertical AP coverage and are difficult to locate in the field, as degradation and sediment transport have resulted in burial of the stumps (fig. 7.4). These posts were located by detailed inspection of tidal drainage channels, sediment probing and individual excavation. Posts were cut from hazel, ash and oak and supported wattle panels. Wooden traps formed single "V" shapes, with arms 40 to 200 metres long. ^{14}C dating of posts from Greyabbey Bay indicates operational dates between the C8th and C13th AD (O'Sullivan *et al* 1997, & above).

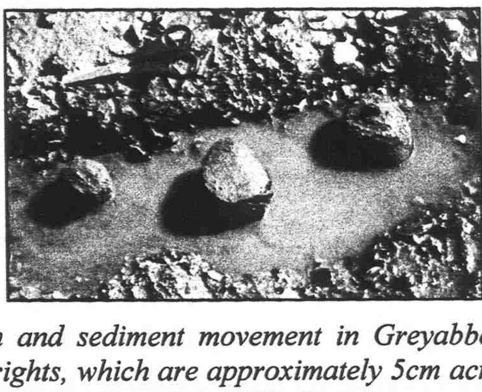

Fig. 7.4: Degradation and sediment movement in Greyabbey Bay has completely covered these weir uprights, which are approximately 5cm across and extremely soft. Wooden weirs in this state are extremely difficult to detect, even in the field.

Stone weirs were easily located from aerial coverage of the area (fig. 7.5); they form either simple V shapes on open areas of shoreline, sickle shapes against the shore, or single-armed barriers linking the sides of eroded drumlins ("pladdies").

Typical arm length was 50 to 300m. These stone traps were constructed with one to three courses of stone enclosing a rubble fill, all built upon a loose foundation of small stones. There were definite kerbs to either side of the wall to aid passage of the workers. Trap height is thought to have been 50cm to 1m, which reflects the low tidal range by comparison to areas such as the Menai Straits, where walls 3m in height were necessary. In one location, a stone trap overlies the remains of a wooden weir structure, suggesting that the stone traps succeed those built from wood.

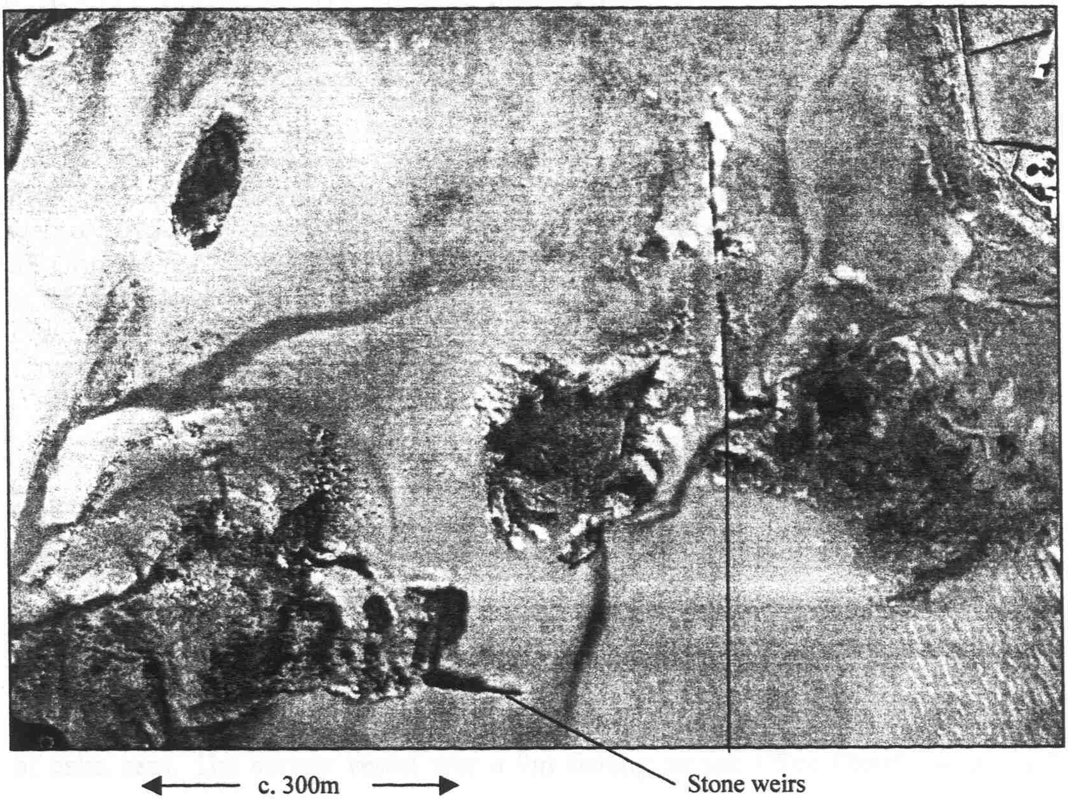

Fig. 7.5: Stone weirs in Strangford Lough are easily identified on vertical aerial photographs. In this picture of Northeast Greyabbey Bay, a hierarchy of simple V shaped weirs is located on or close to inter-tidal drainage channels.

7.4: Geophysical Survey

Relatively easy access and the presence of strong linear structures make the area to the south and west of Greyabbey ideal for testing of inter-tidal side scan sonar. Local vessel availability dictated that only traps providing 1.3m clearance on Spring tides could be approached; three targets in the area were thought suitable: to the east of Chapel Island, to the east of South Island and on the south-east shore of Greyabbey Bay (fig. 7.6).

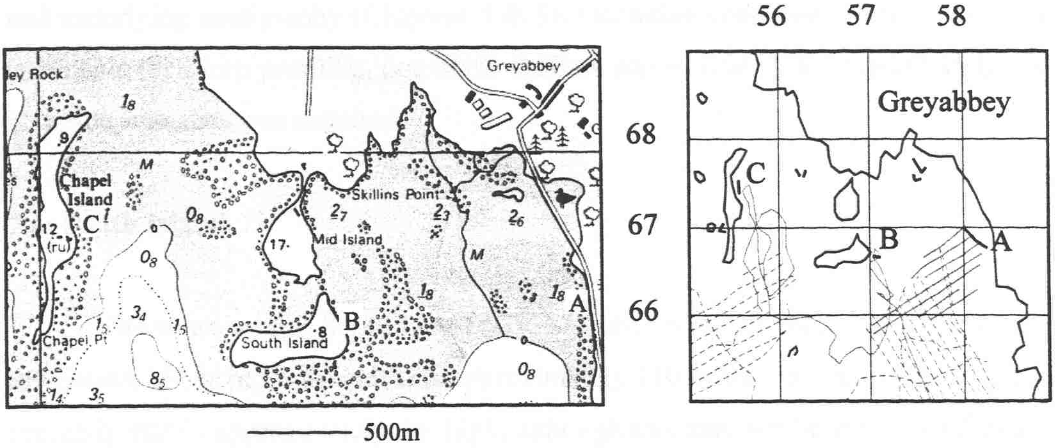

Fig. 7.6: Left: Reduced Admiralty Chart 2156 showing bathymetry to the south & west of Greyabbey and the location of the target structures: (A) sickle-shaped weir in SE Greyabbey Bay, (B) linear weir east of South Island & (C) sickle-shaped trap east of Chapel Island.
Right: Geophysical coverage plot. 500 kHz side scan is indicated in solid grey ink, Chirp & 100 kHz is dashed. Selected traps within the area are represented in black.

Preservation of ancient trees at elevations approximate to MLWS suggests that structures dating to the Mesolithic might lie within the shallow subtidal zone of Greyabbey Bay. In addition to system calibration within the inter-tidal zone, combined 500 kHz and 100 kHz side scan sonar coverage was applied across the subtidal within Greyabbey Bay and to the Southwest of Chapel Island (fig. 7.6).

Surveys were conducted on the highest tides of late May 1997, during a period of calm seas. The survey vessel was a 9m fishing smack ("Sea Otter") with a 1.3 metre draft. Vessel manoeuvrability whilst towing 12 metres of survey catamaran & streamer at close to minimum draft, on a falling tide, was a major unknown, despite several days of testing in deeper water. Reconnaissance at low tide revealed a number of hazards, such as pladdies and scattered glacial erratics. For safety, these were marked with poles and buoys at low tide, prior to survey, although the risk of grounding remained serious.

A total of 19km of 500 kHz data was acquired within the Greyabbey / Chapel Island survey area. At Chapel Island and Southeast Greyabbey Bay, conditions were ideal, facilitating multiple passes at the target, whilst the South Island survey was complicated by the need to approach via a specific submerged corridor. The target was eventually reached, but falling tides resulted in several groundings. It had been intended to acquire Chirp data over these sites, in order to relate the fishing structures and underlying stratigraphy (Chapters 4 & 5). Operating conditions were found to be unsuitable for Chirp profiling, due to the shallow survey draft; consequently only 500 kHz side scan data was acquired.

7.5: South Island

The stone weir at South Island (GR 571 668) is located between a pladdy and the Eastern shore of the island. It is approximately 110 metres in length (fig. 7.7) and presently stands approximately 1m high, although this may not be the original extent of the weir, as subsequent to its abandonment, the weir was partially reconstructed by a local farmer. On the highest spring tide, water depths around the weir are approximately 2.5-2.8 metres; site elevation is therefore approximately 0.8-0.9m OD. The weir is thought be of medieval age and is linked to the nearby presence of the Cistercians at Greyabbey. The weir overlies an earlier, wooden fishing structure, which nowhere protrudes significantly from the seabed and would not therefore be detectable using side scan sonar. A number of ancient tree trunks up to 3.5 metres in length are located 30-50m to the south-east of the fishing weir. These have been ^{14}C dated to c.8000 BP (6000 BC); they are extremely soft and barely protrude from the mud in which they presently lie. The local sediment cover is soft grey estuarine mud, which fills depressions in the eroded drumlin-top till, although sand has accumulated behind the weir and in the channel which links the weir to the main body of Greyabbey Bay at low tide. Access to this site is via this channel, which upon approach to the site, is flanked by large boulders eroded from the glacial till.

The site was successfully accessed during high tide, although navigation along the submerged channel was difficult. A clear side scan image of the weir (fig. 7.7) was obtained during exit from the site. Smearing of the image in places was the result of the sharp turns necessary during re-location of the channel. Neither the wooden posts, nor the ancient forest were detectable, due to lack of protuberance above the seabed.

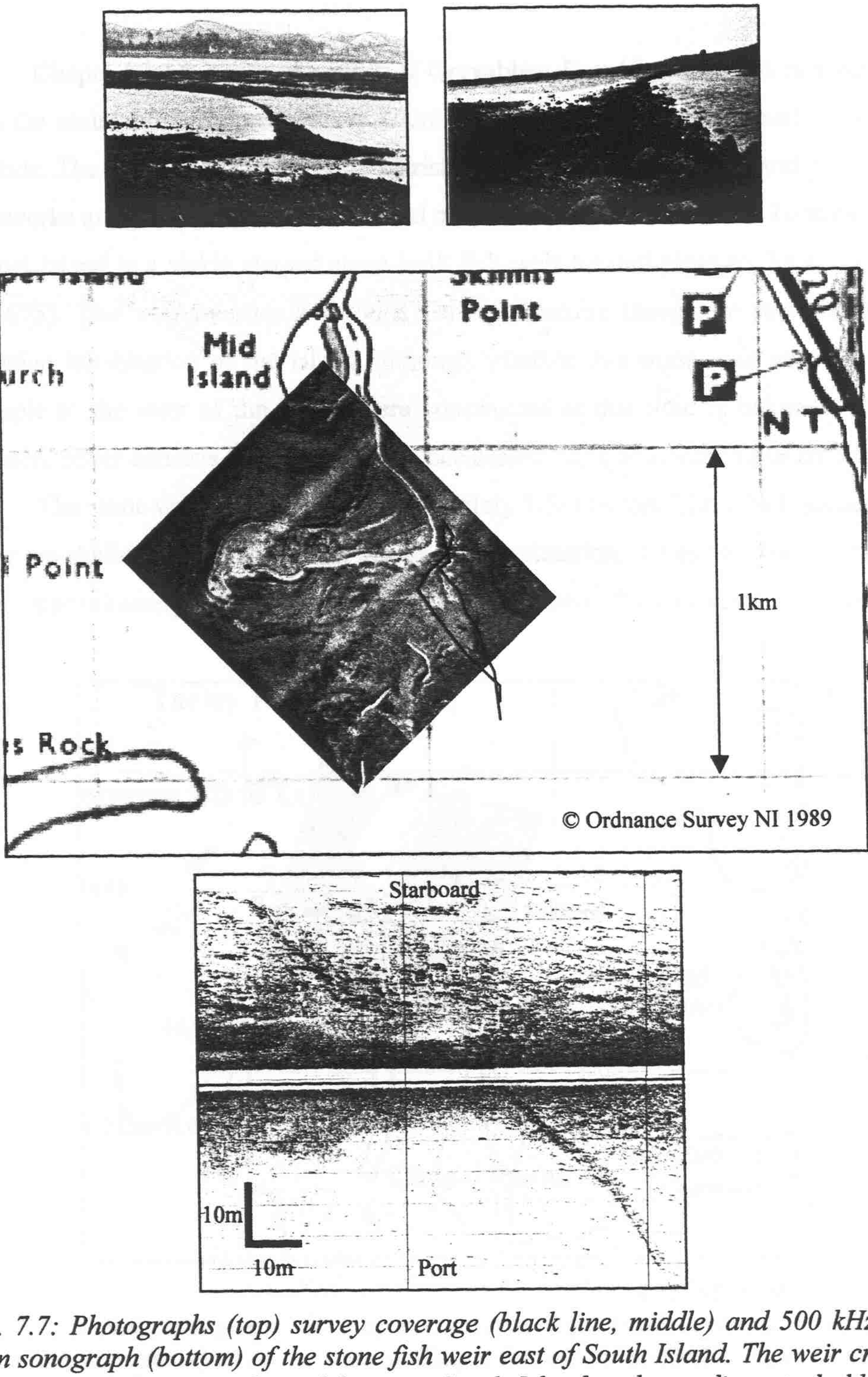

Fig. 7.7: Photographs (top) survey coverage (black line, middle) and 500 kHz side scan sonograph (bottom) of the stone fish weir east of South Island. The weir crosses an inter-tidal drainage channel between South Island and an adjacent pladdy (top left, centre right) and is approximately 110 metres in length. Smearing of the starboard return is a result of vessel manoeuvring within the channel confines.

7.6: Chapel Island

Chapel Island lies to the west of Greyabbey Bay (fig. 7.8) and is separated from the mainland by approximately 800m of mud, which can be crossed on foot at low tide. The foundations of an Early Christian stone chapel, enclosure and associated earthworks are located at the southern end of the island (Hamlin, 1997). To the east of Chapel Island is a sickle shaped stone-built fish weir located close to the shore (GR 556 675). The weir overlies a wooden fishing structure thought to relate to Early Christian inhabitation of the island, although whether this stone weir and a second example to the west of the island were constructed at this time is unknown. Local sediment cover consists of soft mud, with occasional large boulders of glacial origin.

The stone weir is located at approximately 1.5-3 metres OD, which placed it in water too shallow for survey vessel access. In this situation, it was necessary to survey a line approximately parallel to the structure until forced off by shelving bathymetry.

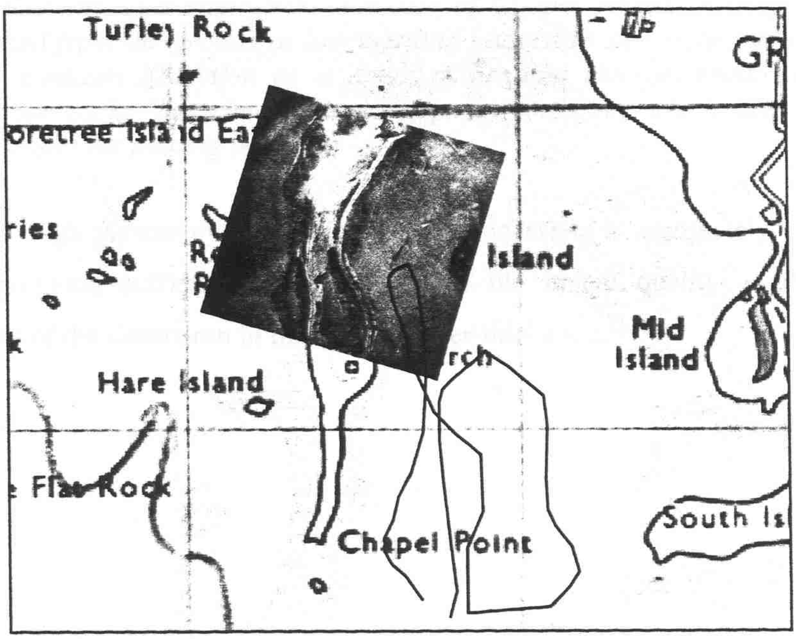

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Fig. 7.8: Aerial photograph, OS map section and ship's track covering the area of a stone fish weir surveyed to the east of Chapel Island, Strangford Lough. The weir is located in the centre of this image, where the coverage track line (black) turns sharply through 180° to avoid grounding.

Lack of sufficient draft for vessel passage was problematic over this site. Despite having pre-placed marker buoys on the larger local obstacles, close approach to the weir was still too dangerous. A short section of the southern extent of the weir was successfully imaged, by making a distant pass with 500 kHz side scan sonar. Although the sonograph (fig. 7.9) has been distorted by vessel motion, the image is of sufficient clarity to detect individual boulders around the site and also the presence of two gaps in the wall of the weir. These gaps are thought to have originally held catch baskets, or nets (McErlean, *pers. comm.*).

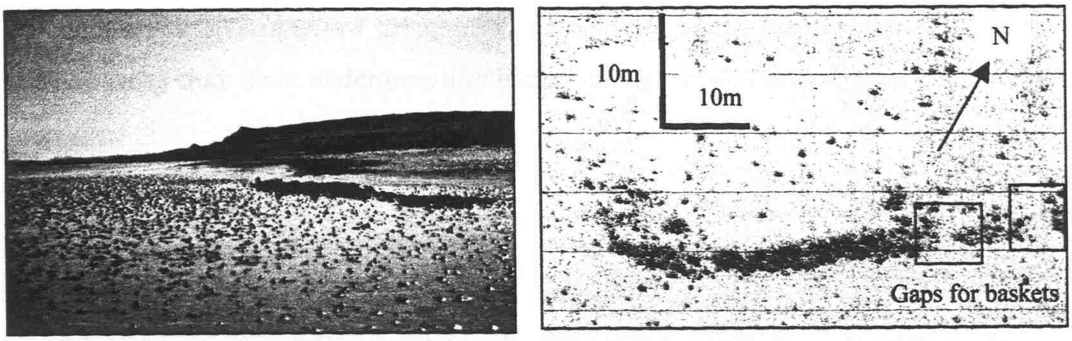

Fig. 7.9: Sections of a stone fish weir east of Chapel Island, Strangford Lough, photographed from the ground at low tide and imaged in side scan sonograph. The sonograph contains distortion as a result of heading changes required to avoid grounding on rocks, but clearly shows gaps in the weir, which are thought to represent spaces for placing baskets.

Although the survey of this site was not successful in completely imaging the weir, it provided sufficient demonstration of the image quality available from deployment of the catamaran in the shallow inter-tidal zone.

7.7: Greyabbey Bay

The longest trap surveyed in Strangford Lough is located on the south-east shore of Greyabbey Bay (GR 583 668). The trap is approximately 300m in length and 0.5 metres high (fig. 7.10). Local sediment cover is sand, which has spread only recently across the Greyabbey Bay area (Ryan & Cooper, 1998), covering previous deposits of mud. This change is typical of the changing conditions resulting from tidal circulation within Strangford Lough, and demonstrates how the inter-tidal maritime sites of today may have undergone significant change since their original occupation or use.

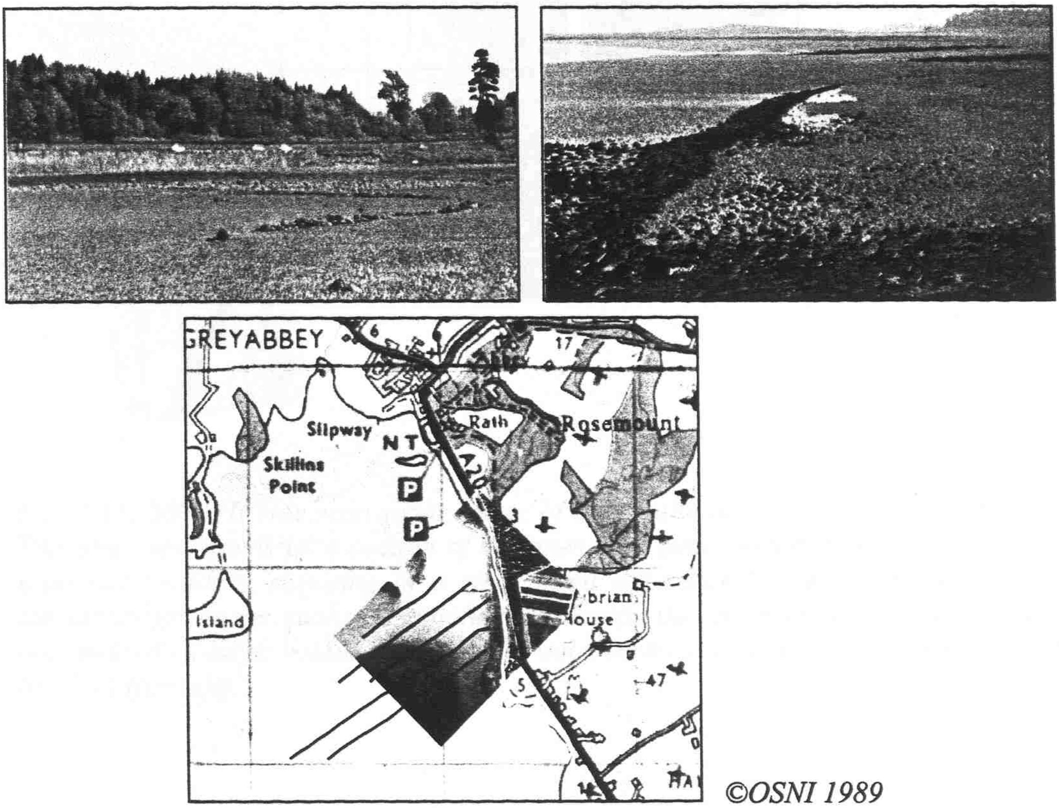

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Fig. 7.10: (Top) The remains of a sickle-shaped stone fish weir, which is located in the south-east of Greyabbey Bay, Strangford Lough (bottom). This weir is approximately 300 metres in length, although the central section (above right) is no longer visible. Track lines completed during seismic survey are indicated in black (above).

Conditions within this area were found to be ideal for a shallow survey: good water visibility and a sandy seabed, which allowed safe passage across the site. A series of parallel survey lines were executed (fig. 7.10), acquiring data which facilitated construction of a composite image of the stone fish weir (fig. 7.11). The discontinuous nature of this weir and the relatively featureless seabed around it, enabled more rigorous ground-truthing of the data. A site visit during the subsequent low tide allowed photography and comparison with the sonographs. Comparison of figures 7.11 and 7.10 demonstrates that features such as landward widening of the weir, intermittent gaps and individual boulders adjacent to the weir are correlatable between field photographs and sonograph.

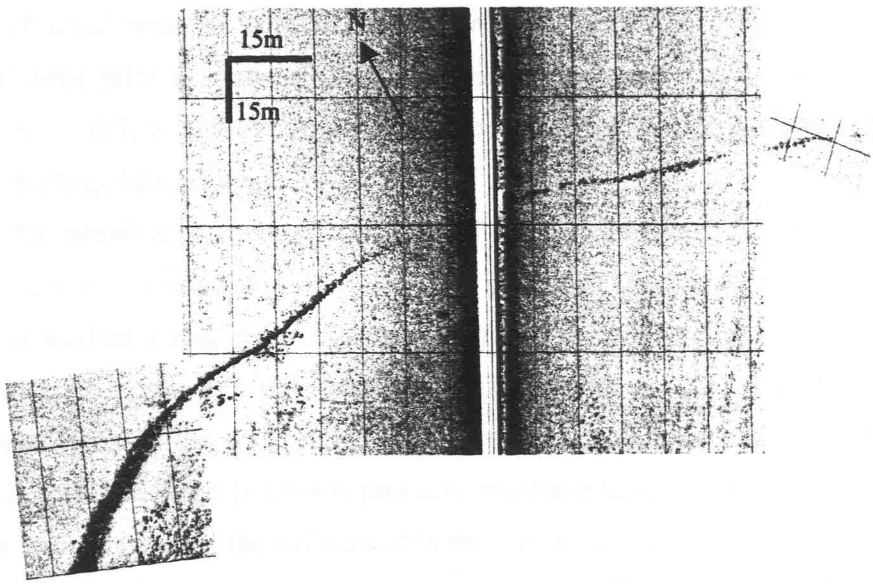

Fig. 7.11: 500 kHz side scan sonar image of the south-east Greyabbey Bay fish weir. This structure stands on a section of the inter-tidal zone, which is relatively clear of scattered boulders, resulting in a clear tonal difference between the trap and its surroundings. Image quality is sufficient to identify the "missing" section of weir and also individual large boulders around the weir, such as those set in the foreground of fig. 7.14 (top left).

7.8 Discussion of Results from Strangford Lough

Results from the calibration exercise in Strangford Lough were extremely positive. Data gathered from the three sites surveyed indicated that a catamaran-mounted, 500kHz side scan sonar system is capable of clearly resolving stone structures within the inter-tidal zone. Subsequent inspection of the sites during low tide shows that often the system can isolate individual boulders, which have been dislodged from the weirs. This question of resolution was a serious concern, as the effect of small amounts of swell and prop wash upon the catamaran had been unpredictable prior to system testing. The catamaran was found to provide a solid base from which to survey, whilst subsequent navigation tests indicate only small errors resulting from yawing.

No additional structures were located within the sub-tidal zone of the area surveyed, nor within the area covered by the combined Chirp and 100 kHz side scan survey described during chapter 5. Two anomalies located 7km to the south-west of Chapel Island, in 20m of water, were found to represent a 4m boat and light aeroplane wreckage dating to the early 1990's. The quality of the images recorded over these anomalies and the stone fish weirs provides reliable evidence that no large structures remain undiscovered on the seabed within the area surveyed. The ability to determine an absence of archaeologically important structures within an area of seabed, using a rapid survey method, is as important in site survey and management terms as that of unequivocally locating such material when it is present. It will be important during future work to examine the limiting conditions for which side scan sonar can be relied upon to detect archaeological targets, as it may become a major tool for rapid assessment of inter-tidal areas. Rapid seabed prospection might be viewed as financially desirable by developers required to conduct archaeological survey, but the reliability of this technique must be rigorously established, if the coastal resource is to be adequately protected.

7.9: Inter-disciplinary prospection and mapping of drowned wooden structures in the Blackwater Estuary: Introduction

The Blackwater Estuary is the largest in Essex and amongst the greatest estuarine complexes in East Anglia. The estuary is 23km in length, from Maldon at its head, to the mouth, located between Sales Point and the East Mersea Flats (fig. 7.12). Local topography is subdued; land within the area only exceeds 15 metres above OD at one point 5km NW of Maldon - the 40m high Danbury-Tiptree escarpment.

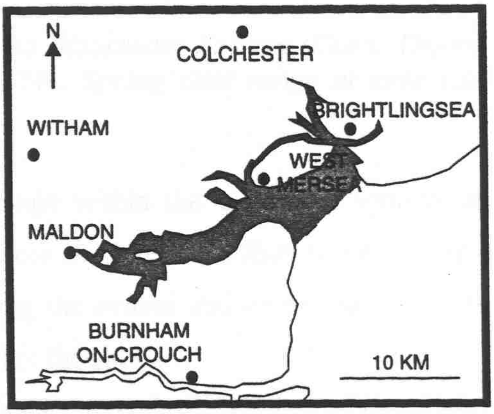

Fig. 7.12: The Blackwater Estuary, Essex (shaded) is approximately 23km in length and typically 2-3km across. Principal towns of the area are Maldon at the estuary head and West Mersea, close to the mouth.

The drying area of the mudflats within the river limits is an internationally designated waterfowl habitat, a Special Protection Area within EEC legislation and an SSSI under the national Wildlife and Countryside Act of 1981. Most of the inter-tidal area consists of mudflats bordered by extensive saltmarsh; the mud is generally extremely soft and large expanses are impassable on foot. Some areas of the inter-tidal zone exhibit a flat topography, whilst others are incised by drainage channels, shingle and shell banks producing topographic irregularities of ±2m or more. The width of the inter-tidal zone is variable throughout the estuary; the greatest expanses presently occur around the Collins Creeks within the estuary and at the estuary mouth seaward of Mersea Island and St. Peter's Flat, off Sales Point. The former two areas are typically 1.5 km wide, whilst St Peter's Flat attains widths of 4.5km.

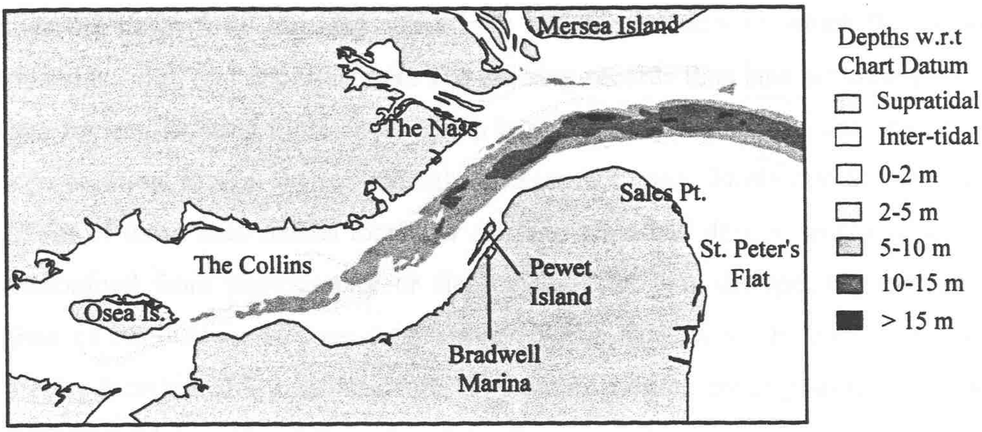

Fig. 7.13: Bathymetry of the Blackwater Estuary, Essex. Depths are extracted from HMSO Admiralty Chart 3741. Spring tidal range at sites east of Osea Island is approximately 5 metres.

The spring tidal range within the estuary is approximately 5 metres. Low gradient beach profiles across the inter-tidal flats results in rapid transgression with the returning tide, rendering the central and outer reaches of these areas artificially remote and inaccessible from the shore.

The Blackwater Estuary contains a number of important archaeological sites dating from the Neolithic and later. The area has a strong tradition of inter-tidal survey, exemplified by the ongoing Hullbridge Survey, which has explored and documented numerous sites, including the well known prehistoric settlements at the Stumble, near Osea Island (Wilkinson & Murphy 1995, Fulford *et al.* 1997). The sites of interest to this report are wooden fishing weirs, which have undergone a gradual rediscovery during the past 25 years. At present, six weir complexes have been properly identified, although ongoing aerial survey continues to yield locations for further investigation. The main sites are located at Pewet Island, East and West Mersea, Pewet Island, Sales Point and The Collins. These sites are located above and below MLWS approximately 300m to 1.5km offshore; the only site easily accessible from land is the upper area of the Pewet Island structures. It has been observed (Wallis, 1993) that this estuary has undergone less dredging than its contemporaries (e.g. Thames, Crouch), and is thus more likely to contain intact timber structures.

The potential to map the wooden weirs of the Blackwater Estuary was considered beneficial to the local archaeology on two fronts. The existing SMR[2] contains photographs of the weirs on some of the lowest tides this century, yet certain

[2] Sites and Monuments Record

sites are never fully exposed subaerially and the window in which they might be visited is small and unpredictable. The existing records thus lack accurate positioning data for geo-locating these sites, which is a necessary element in site protection and incorporation to any environmental management plan. Furthermore, the unknown extent of these sites means that their original scale and design cannot be accurately determined from photography or field visits. The two site-specific archaeological aims of conducting an inter-tidal survey in the Blackwater Estuary were thus the precise location of known structures by combination of aerial photography and side scan sonar data, and a full exploration of any structures located in the shallow sub-tidal zone.

7.10: Local Geology

The geology of the Chelmsford district is described fully by Bristow (1985). The Blackwater Estuary is underlain by Lower London Tertiaries, although the oldest outcropping formation within the valley is the Eocene London Clay, the base of which lies at c. -35 to -45m OD, throughout the estuary. Regional structure is dictated by the London Basin syncline, whose east-west trending axis is located 15km south of the estuary. Consequently, the youngest strata are exposed to the south-west, in the Danbury-Tiptree escarpment (5km west of Maldon).

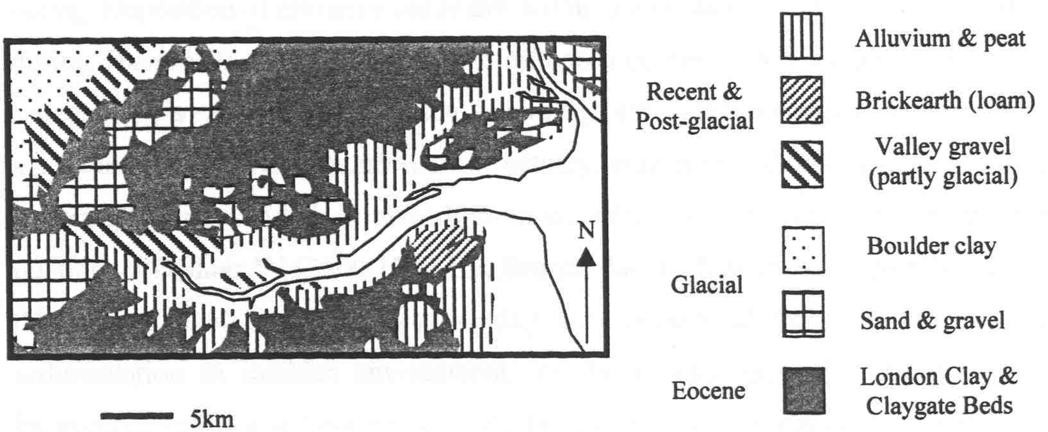

Fig. 7.14: Geological sketch of the Blackwater Estuary area. Source: Ordnance Survey (1931). The Blackwater valley consists of terraced alluvium overlying Eocene London Clay and Claygate Beds. Auger and borehole surveys suggest that the clay deposits lie within 15 metres of the surface around the estuary (Greensmith & Tucker 1971, Bristow 1985) and constitute acoustic basement to the Chirp pulse.

Much of the Blackwater valley is covered by terraced glacial and post-glacial drift deposits, which relate to Pleistocene glaciation. Fluvial and marine activity is thought to have deeply eroded these deposits within the estuary, and it has been suggested (Greensmith & Tucker, 1971) that the London Clay generally lies extremely close to the seabed. A borehole drilled 0.5km off Bradwell proved London Clay at 5.5m below the surface, whilst outcrops of the clay are described close to Bradwell Power Station (GR 6002 2090) and north-west of Tollesbury Wick. A thickness of 13.7 metres of superficial sediment has been proved above London Clay on the marshes of the Wick (Greensmith & Tucker, 1971).

Wilkinson & Murphy (1995) discuss the Flandrian estuarine sedimentation of the Blackwater Estuary in some detail, proposing that reed swamps, mudflats, salt marshes and fen woods would have provided a range of habitats suitable for exploitation by early communities around the Thames, Crouch and Blackwater estuaries. Five phases of marine transgression (Thames I-V), characterised by the deposition of predominantly mineral estuarine/marine sediments, are identified; these phases relate to isostatic recovery, North Sea subsidence and eustatic sea level oscillations during the Holocene. These are divided by five phases of regression (Tilbury I-V), characterised by the formation of biogenic deposits. Evidence for the onset of the Thames II transgression is observed in the Blackwater at Bradwell on Sea, where a basal peaty deposit formed in estuarine conditions has been recovered by coring. Deposition of estuarine sediments within the modern tidal range was occurring during Thames III (4000-3500 BP, and reflects a comparatively simple transgressive sequence. It is suggested (Wilkinson & Murphy, 1995) that transgression represented a tranquil, progressive expansion of the estuary, with zones of saltmarsh and mudflat spreading laterally and diachronously from the valley axis. Deposits in the Blackwater relating to Thames IV (3500-1750 BP, Bronze Age to Roman) are typically uniform thick deposits of grey clay, representing long periods of uninterrupted estuarine sedimentation in mudflat environments as the estuary gradually expanded. The intervening regression between Thames IV and V does not appear to occur in the Blackwater, where deposition of estuarine mineral sediments appears continuous to the present day.

7.11: History of Exploration in the Blackwater Estuary

The current wave of archaeological interest in the inter-tidal areas of the Blackwater Estuary was initiated by the chance observation of parallel lines of posts on The Collins, by local boatman Ron Hall in 1989 (Hall, 1997). The Collins was used extensively as an RAF bombing range during both World Wars and it was initially supposed that the posts represented the remnants of an abandoned Ministry of Defence project. Closer inspection revealed vertical wooden stakes, 100-150 mm in diameter, set into parallel lines along shingle ridges and across impassable muddy inlets. Hall was uncertain as to the purpose of these structures and unaware that local archaeologist Kevin Bruce had photographed similar structures at Sales Point in 1967 and measured them during 1974. Bruce's independent investigation had mapped arrays of similar posts within the inter-tidal zone to the east of the chapel of St Peter-in-the-Wall. Complementary historical research revealed reports from 1906 suggesting the presence of a drowned roadway lined with stakes, lying between Mersea Island and Bradwell-on-Sea (Bruce 1993 & *pers. comm.* 2000).

In 1991, Hall's purchase of the *Olan,* a flat-bottomed steel workboat, facilitated safe site visits, resulting in the compilation of a rough survey map for the area. This map attracted the Essex County Council Archaeology Section (ECCAS) to the site and triggered interest in the inter-tidal zone on a greater scale, although an area approximately 1km x 2km surrounding the Collins Creeks remained the focus of activity within the estuary.

Wood samples from the Collins structure were ^{14}C dated during 1991, indicating a probable Saxon origin (640-675 AD and 882-957 AD) (Groves 1993, Strachan 1997, Hall & Clarke *in press*). Comparison with the local RSL curve showed that the most likely purpose for these structures was for use as fish traps, although the parallel nature of the structures differed from those of the Severn Estuary - the only weirs of similar size identified within the UK. The lack of any visible ancient land surface or horizons indicative of a salt marsh environment, coupled with the sea level curve suggested that these weirs would have operated in an inter-tidal environment.

Subsequent terrestrial investigation focussed upon the site at the Collins, which was found to be rapidly eroding. Work on this site included the acquisition of vertical aerial photographic coverage, ^{14}C dating (Strachan, 1997), investigation into dendrochronology (Groves, 1993) and the preparation of a detailed site map by terrestrial DGPS techniques (Dare 1994, Hall & Clarke *in press*). Meanwhile, greater publicity created local interest and attracted Kevin Bruce to the expanding Blackwater Estuary survey team. A wider scale aerial investigation of the Blackwater during 1992-1993 resulted in the discovery of five additional sites within the estuary, containing large wooden structures (Pewet Island, East and West Mersea, Pewet Island & Sales Point). The Essex Sites and Monuments Records (SMR) contain all of the available photographic evidence from these sites. Existing records suggest that the six major recorded structures differ greatly in form, including major structures without simple shape (Collins Creek), simple "V" shaped weirs (West Mersea & The Nass) and rectangular weirs with closure at one corner (East Mersea & Sales Point) (fig. 7.16). The features observed at Pewet Island appear to comprise two distinct weirs, approximately 300 metres apart. Tides utilised by this program included some of the lowest ebbs this century (Crump & Wallis 1992, Wallis 1993, 1994), yet it is apparent that some of the structures extend below their recorded limits and can be regarded as permanently submerged. Work on individual sites is described in further detail below.

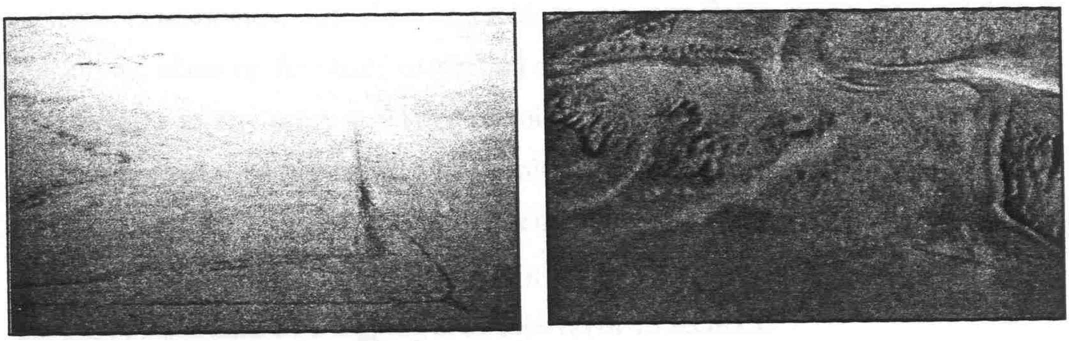

Fig. 7.15: Aerial photography (Strachan) of the East Mersea Flats (left) and Collins Creek weir complexes, showing the range of fishing structure construction in the Blackwater Estuary, from simple 'V' shaped weirs to complex arrangements of shore-parallel lineations built on elevated shell ridges.

Since the intensive projects of the early 1990's the area has undergone biannual equinoctial aerial survey, by David Strachan (working for Essex County Council), improving the range and content of the SMR for this region (Strachan 1995, 1997, 1998). The need for additional, future work in the estuary is noted in Management Plans for the Greater Thames and Blackwater Estuaries (Strachan 1996, (Williams & Brown 1999). Aerial reconnaissance of the estuary on twice-yearly low spring tides continues and often results in the discovery of isolated post lines in new locations.

7.12: Geophysical Survey

Marine geophysical survey of selected archaeological sites within the Blackwater Estuary was undertaken during May 1998, aboard the *Olan*. Dual frequency (100 / 500 kHz) side scan sonar was deployed over six sites, three of which were also surveyed with the Chirp sub-bottom profiler. Differential GPS utilising the Focus FM™ correction was employed at all times during the marine survey, whilst vertical variation in instrument position due to tides was monitored on a portable water-level recorder, mounted in Bradwell marina.

Survey site locations were initially provided by the approximate geo-location of oblique aerial photographs by David Strachan, of Essex County Council. In the many cases where precise location proved impossible, large survey grids were designed in allowance for positional error. Surveys were scheduled to coincide with the maximum Spring tidal levels, which permitted easy access to all sites without incident. In addition, an aerial photographic survey was flown during the final day of the survey, allowing first-hand inspection of the targets and confirming the presence of structures in any areas appearing devoid of any geophysical anomaly. A second flight was conducted two months later, following preliminary inspection of the data. Description of the aircraft, camera specification and SMR recording system has previously been made by Strachan (1995); approximate positioning was provided by the use of hand-held GPS logging at an interval of 15 seconds.

Approximately 100km of 500 kHz side scan and 25km of combined 100 kHz & Chirp survey coverage was acquired across five survey days (fig. 7.16). Survey conditions were generally fine, with flat calm water over the inner estuary and up to 0.5m of sea swell during the second day spent at East Mersea Flats.

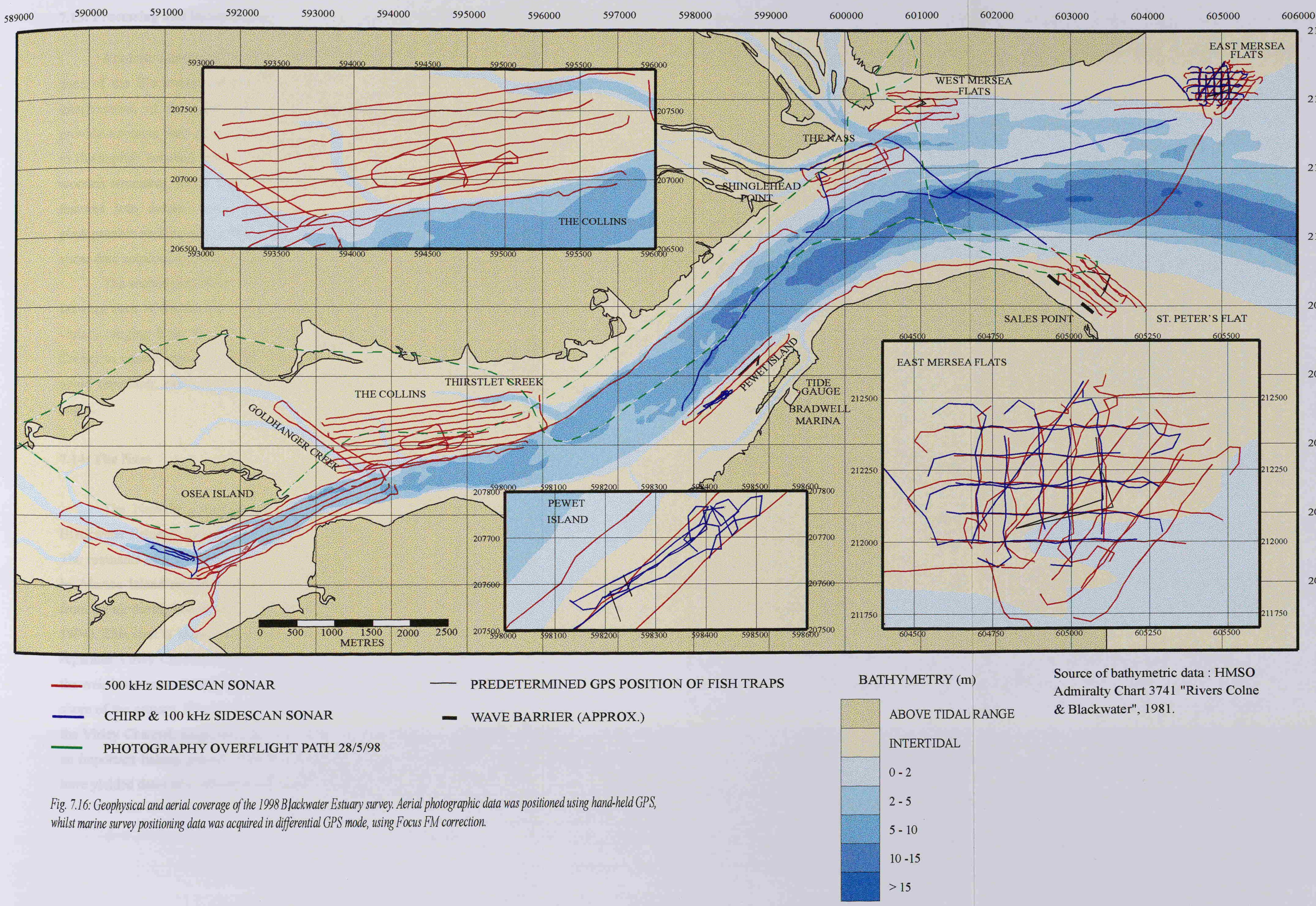

Fig. 7.16: Geophysical and aerial coverage of the 1998 Blackwater Estuary survey. Aerial photographic data was positioned using hand-held GPS, whilst marine survey positioning data was acquired in differential GPS mode, using Focus FM correction.

7.13: Processing and Interpretation

Accurate interpretation of side scan sonar data acquired within the intertidal zone of the Blackwater sites has been found to be an iterative process involving interpretation of the associated oblique aerial photographic record. Photographs provide a remote form of ground-truthing for side scan data, enabling the interpreter to distinguish between linear anomalies created by gravel banks, cheniers etc. and wooden structures, in the higher intertidal zone and to subsequently continue these features into deeper water. Essex County Council made available the entire photographic archive of the Blackwater estuary SMR, for interpretation of side scan sonar data acquired within the estuary.

The seabed conditions and structural composition of the weirs differed greatly between each of the six sites. The amount of available background information also varied, ranging from sites with terrestrially measured DGPS co-ordinates (Collins Creek) to others where the SMR is virtually bereft of data (e.g. West Mersea). To avoid repetition, each site is treated as an individual case study on the following pages.

7.14: The Nass

The Nass is a narrow peninsula located upon the northern shore of the Blackwater Estuary, approximately 1km south-west of Mersea Island (GR 600 211). The remnants of a stationary wooden fishing structure at this location were reported by Mersea Island residents during the early 1990's and subsequently photographed from the air during one of the lowest tides of the century, during March, 1993 (Wallis, 1994). This weir is located 1km NE of Shinglehead Point on a low-lying area which separates Virley Channel from the main estuary. Drainage from the site is rapid and the weir is the most commonly exposed example of such a structure from the northern shore of the estuary. Wooden structures have been also reported on the north bank of the Virley Channel, suggesting that this region of the northern shore was historically an important fishing ground. Carbon dating of oak and hazel timbers from the weir have yielded dates of c. 664-862 AD and 690-882 AD (Strachan, 1998).

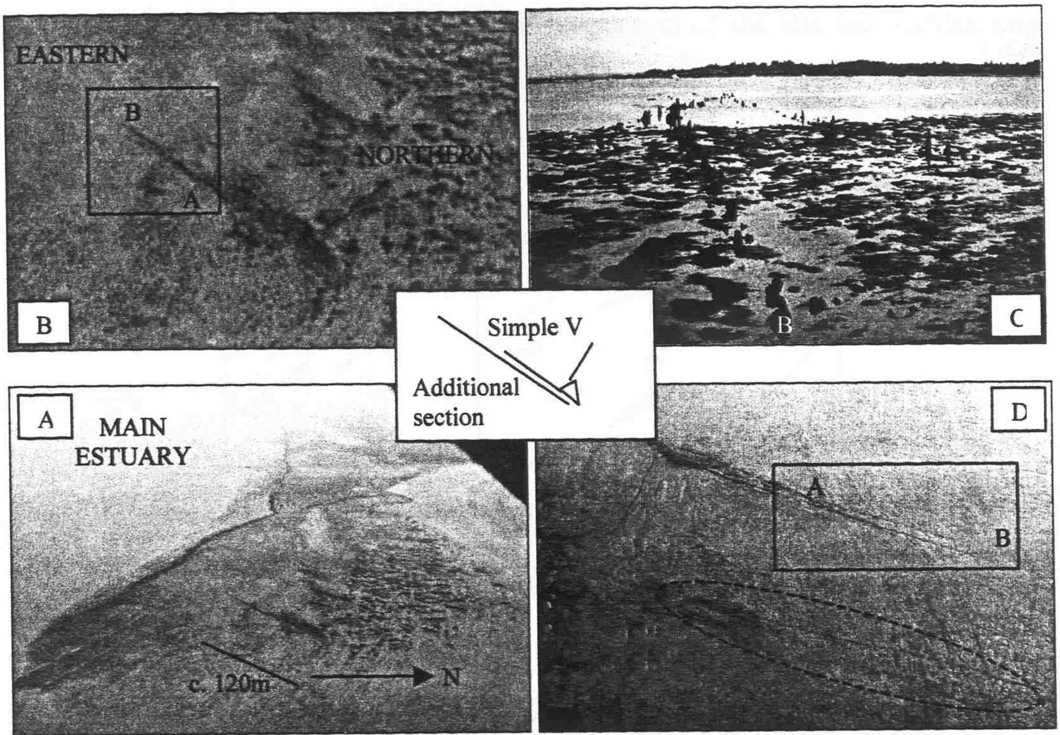

Fig. 7.17: Aerial and terrestrial oblique photography of the wooden fishing structure on the Nass. (A) The Nass weir is located on a narrow point between the main estuary and Virley Channel. The point is covered by soft featureless mud to the south, but in the north bedforms containing coarser sediments flank the weir. (B) The apparently simple weir structure consists of two contrasting arms; the shorter northern arm is a concentrated mass of stakes, whilst the eastern arm comprises several sub-parallel linear structures. It is possible to identify a simple central V shaped structure isolated from the main eastern arm (see central sketch). (C) The open end of the eastern arm showing interlocking lines of uprights. (D) Reverse aerial view of the weir.

Aerial and terrestrial photographic interpretation by Strachan (1997) suggests that the weir possesses a central simple "V" structure (fig. 7.18), whose apex points roughly north-west, plus additional post lines on the eastern limb, extending the weir southwards (fig. 7.17B). The central weir arms are short, extending approximately 50 metres; the total length of the extended eastern arm is approximately 120 metres. The surviving uprights protrude approximately 30-40cm above the seabed in places. In addition to the main V-shaped weir sketched by Strachan (1997, see fig. 7.18), aerial photographs suggest an additional lineation (fig. 7.18 *bottom right - in ellipse*) approximately 100m to the west of the weir, which appears to create a square-bottomed "U" shape. It is possible that this lineation represents the remnants of a walkway from the higher ground behind the trap to the end of the northern arm, which is the logical location for access to the weir at any state of tide. Bruce (1993) suggests that this additional section formed a second trap, operating on the flood tide, although the mechanics of this are uncertain. Field inspection of the site has yielded large amounts of scattered wattling panels, but it is impossible to determine whether these represent walkways, or disintegrated sections of the weir walls.

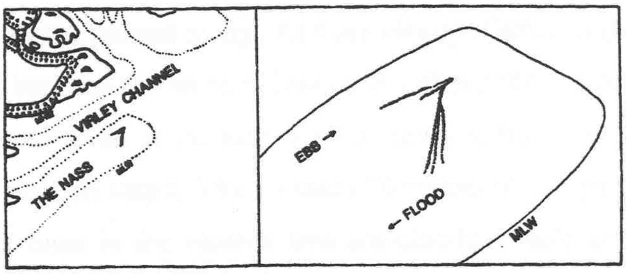

Fig. 7.18: Sketch of the wooden fishing structure on the Nass composed from aerial and terrestrial photographic evidence, by Strachan (1997). The site is located on a low-relief mud bank between the Virley Channel and the main estuarial channel.

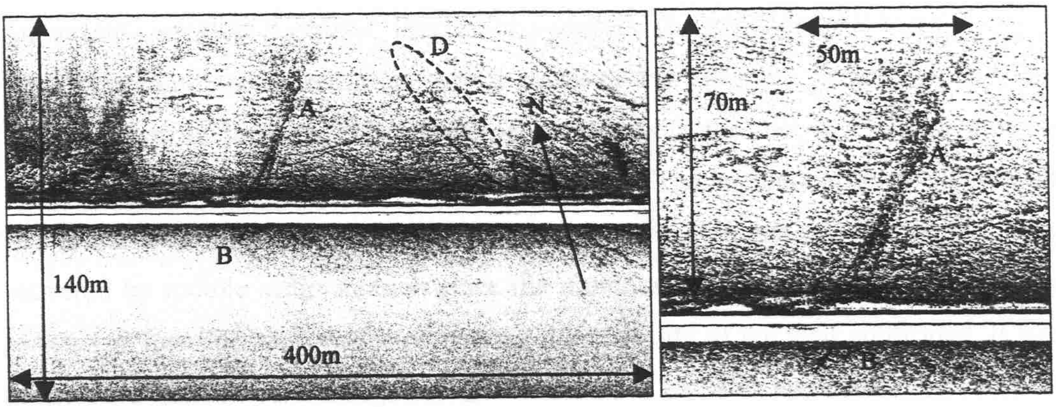

Fig. 7.19: Side scan sonographs showing the eastern arm of the Nass fishing weir. Note noise on the port channel caused by turbulence around the catamaran, which obscures the seabed arrival in shallow water. The north-south sedimentological contrast across the point is clearly represented on this record (left). The sub-parallel nature of lineations within the eastern arm is clearly imaged where the sediment cover is featureless (right), but image quality rapidly diminishes in the less uniformly reflective northern section. Dredge scars left by local oyster fishermen (D) are clearly visible close to the weir.

Side scan survey of this site comprised a simple set of six parallel lines (fig. 7.15) at a spacing of 100m. Total track length was 7km, corresponding to 0.7km^2 of side scan coverage, acquired in 90 minutes. In addition, an oblique aerial photographic flight was conducted over this site, during the four-day Blackwater estuary survey.

Results from this rapid survey are generally significant in the evaluation of the applicability of side scan sonar to sites within the Blackwater Estuary. The contrast in sediment type and consequent backscatter amplitude across the Nass was observed to exert a strong effect on the probability of imaging wooden structures on the seabed. This is particularly well represented in fig. 7.19, where the individual lineations photographed from the ground in fig. 7.18 are clearly displayed (labelled A-B). The acoustic contrast between the wooden posts and soft muddy seabed results in distinct imaging of the weir, even at the near vertical acoustic incidence angles created by passing directly over the target. The southern 70 metres of sub-parallel and obliquely crosscutting post lines in the eastern arm are clearly visible on this record. Also visible are dredge scars whose likely origins are local fishermen dragging for oysters (fig. 7.19D).

To the north of this survey line, the weir becomes more diffuse in nature and passes into a region of coarser, less uniform seabed. The trap closure is identified only as a concentration of reflection, which crosscuts the sediment pattern, as does the northern arm of the weir. The additional lineations to the rear of the weir are lost within the high backscatter of the coarser sediment. The apparent absence of the weir from this area required ground truthing, as it was possible that this section had been covered by mobile sedimentation since the previous aerial survey. A flight over the estuary at low tide was conducted and the full visibility of the weir confirmed. It was concluded that failure to image the northern limb of the weir was caused by a lack of sufficient acoustic textural contrast between the seabed material and wooden structure.

Sufficient structure could be identified from the side scan images to provide accurate positions for the weir upon the Nass (fig. 7.20). The clarity of images from the southern end of the weir suggests that any structures located on soft featureless sediment in the subtidal zone to the south of this point would be identifiable by side scan survey, whereas only scars from oyster dredging have been detected in this area. North of the Nass, there is a strong possibility that wooden structures on the seabed would go undetected unless they are either strongly upstanding, or cut acutely across the orientation of the strong sediment distribution patterns in this area. Thus the possibility of additional wooden structures within the Virley Channel cannot be discounted, particularly as intertidal remnants of such structures have been observed on the north bank of the channel (Hall, *pers. comm.*).

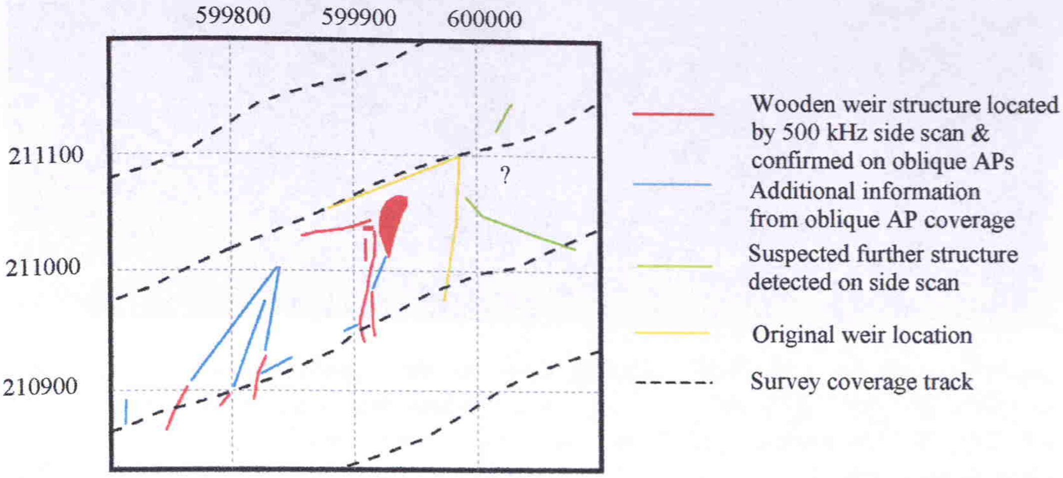

Fig. 7.20: Isometric interpretation of side scan sonar data from the Nass site. Identification of the weir at this site is easiest in the south, where the uprights provide a clear contrast with the surrounding featureless sediment. The northern limb of the weir is sub-parallel to natural sediment patterns in the south channel of Tollesbury Fleet, consequently identification of linear elements here is more difficult. The Nass weir appears to be isolated from any further structures, which might exist in the subtidal, although a striking anomaly cross-cutting the natural sedimentation 100 metres to the Northeast remains unexplained.

7.15: West Mersea Flats

Local residents reported the presence of a fishing weir on the West Mersea flats during 1993 and the site was covered during subsequent aerial survey (fig. 7.21). The weir is relatively small, forming a simple V shape of 100 metre sides, whose apex points approximately east. The weir is thought to have operated as a trap to fish carried out of the channels west of Mersea Island by the ebb tide (fig. 7.22). Although this weir sits relatively close to the shore (fig. 7.21, 7.22), it lies at a lower altitude than its contemporaries and is sufficiently rarely exposed that it is regarded as being subtidal by local archaeologists, who have been unable to visit the site (Strachan, 1997). Active sediment migration from channels to the west of Mersea Island sometimes completely buries this trap, adding to the difficulty of archaeological inspection (Strachan, *pers. comm.*).

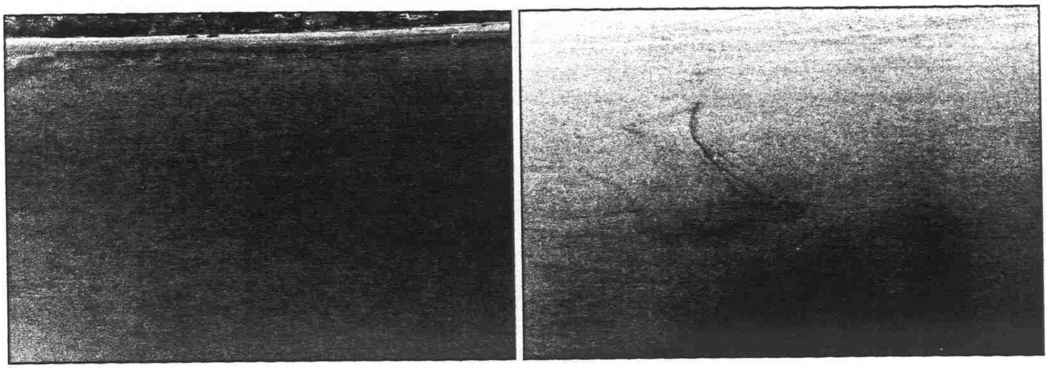

Fig. 7.21: Wooden fishing weir at West Mersea. The arms of this weir are approximately 100m in length and the apex points to the east. Note the effect of sediment migration, which covered a large section of the southern arm in 1992 and was also observed on side scan sonographs of the weir in 1998. No reliable scale indication can be made, due to obliquity of perspective.

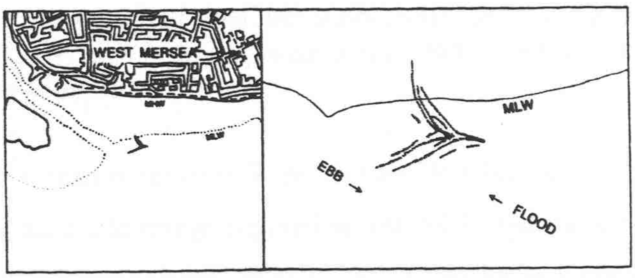

Fig. 7.22: Sketch of the West Mersea Flats fish weir compiled from aerial photography by Strachan (1997). The site is located close to shore, yet is only very rarely exposed and has yet to be visited by archaeologists since its discovery in 1992.

Side scan survey of the area consisted of c. 7km (0.7km^2) 500 kHz coverage, as five parallel lines and two obliques (fig. 7.15). Most of the structure was clearly visible on the records, including some of the more detailed structure to the north of the weir closure. In addition to the main structure, a prominent linear anomaly was detected to the east; this appears to join the main weir at a point 20 metres into the subtidal zone, continuing a section of trap which disappears underwater in fig. 7.21.

The low altitude and extremely infrequent exposure of this site make conventional survey by field walking and terrestrial survey methods impossible. The short survey time necessary for side scan survey (75 minutes) and the possibility of mapping the site at most states of tide make this site very well suited to a marine geophysical approach, in preference to terrestrial mapping.

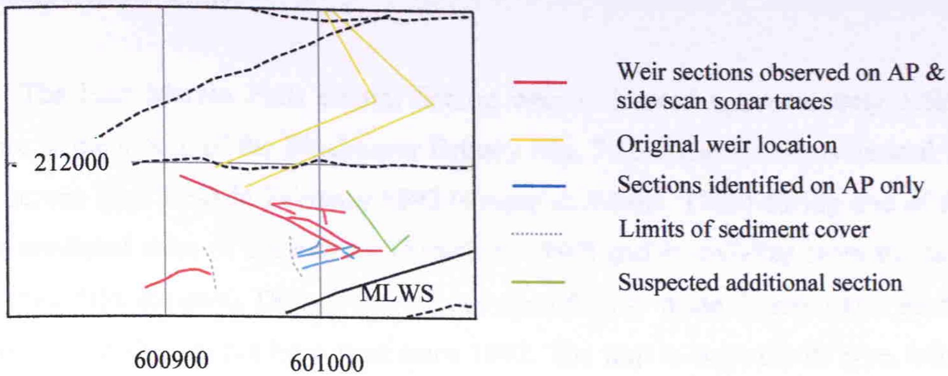

Fig. 7.23: Isometric plot of wooden weir structures mapped on West Mersea Flats. At this locality, there was substantial overlap between anomalies located with side scan sonar and linear weir sections photographed from the air. Combination of both data sets has resulted in an accurate plan of the weir structure and has also produced data suggesting that an additional linear section is located to the east of the known structure. MLWS was extracted from Admiralty data; but is no guide to the altitude of the site, which has not been exposed since 1993 and is regarded by local archaeologists as being subtidal.

Use of side scan sonar over West Mersea Flats has facilitated construction of an accurate plan for a site rarely exposed at low tides, and the discovery of a small additional section of weir. Approximately 80% of the known structure was detected on sonographs; the remainder of the known structure has been located from aerial photographs, by reference to positions obtained from the isometric side scan plots. A probable additional section of weir has been discovered, in a location agreeing with the established general structure. Side scan sonar anomalies from this site are faint, but sharp-edged, suggesting that the arms consist of tight linear arrangements of uprights, with no surrounding related seabed material, such as wattling, which has been observed elsewhere in the estuary (see Sales Point, this chapter).

An important observation from this site is the section of weir apparently missing from the main southern limb. This fifty-metre section does not appear on either side scan or aerial photographic records, yet it is apparent that the trap could not have functioned without it. Close inspection of both records suggests burial by mobile sediments, which form faintly visible banks at the points where the southern arm vanishes. This demonstration of the ability of sediment transport to periodically cover large intertidal sites is highly significant, indicating that sites exposed to occasional increased hydrodynamic energy levels may never be fully mapped, although repeat visits to the area should improve the probability of locating seabed structures.

7.16: East Mersea Flats

The East Mersea Flats coastal fishing weir is located approximately 1.5km offshore at the mouth of the Blackwater Estuary (fig. 7.15). The weir was located by aerial survey (fig. 7.24) in February 1992 (Crump & Wallis, 1992) during one of the lowest predicted tides of the century (Strachan, 1997) and is invisible from the land even when fully exposed. Despite numerous repeat flights at the Autumn and Spring equinoxes, this site has not been seen since 1992. The trap is large for its type, being "V" shaped in general form, with limbs approximately 280 metres in length (fig. 7.24, 7.25). The eye area of the weir appears to have undergone at least three stages of rebuilding (Strachan, 1997).

Lack of information within the SMR and constant navigable water above the site justified a larger survey than those executed elsewhere within the estuary. An investigation was made to assess whether the compilation of contrastingly orientated side scan survey grids is validated by the additional information yielded. Three sets of parallel survey lines were collected at orientations of N-S, E-W and NE-SW, with a line separation of 100 metres. Total 500 kHz track coverage was approximately 12 km ($1.2km^2$ areal coverage). Aerial oblique photography suggested that this site might exhibit a topographic dependency upon the shoreface slope; to investigate this, a combined Chirp & 100 kHz side scan survey was also conducted, forming a grid of N-S and E-W orientated survey lines, also at 100m spacing.

The multiple-orientation side scan sonar survey facilitated accurate mapping of the known East Mersea structure and also detected additional linear features to the north and west (fig. 7.27). Linear anomalies on the northern limb of the weir imply weir dimensions twice those suggested by the aerial survey: each arm of the weir is approximately 500 metres in length. The effect of surveying at multiple line orientations was to significantly increase the information on site structure derived from the sonographs. No single orientation produced sufficient data to map the entire trap structure (fig. 7.26): combination of data from all three orientations facilitated mapping of approximately 80-90% of the structure visible upon the aerial obliques. Image quality at this site was highly variable across short distances (fig. 7.26A). In some areas, the weir was clearly visible and resolvable as two closely spaced linear elements, which aerial study has suggested to represent multiple stages of construction. Orientation-dependent variability in image quality is a recurrent factor throughout the survey data set at all of the survey sites and is discussed in section 7.7.

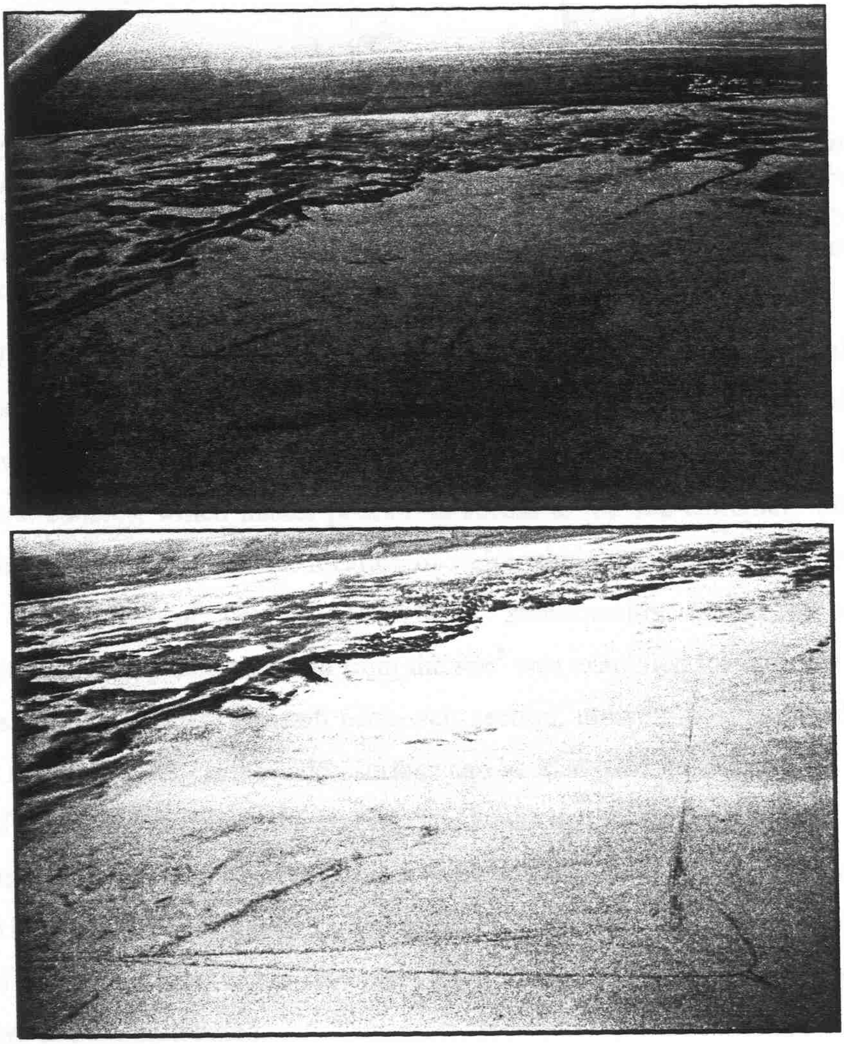

Fig. 7.24: Aerial obliques of the East Mersea weir structures. These photographs comprised the entire SMR for this weir, prior to geophysical survey in 1998. Each limb of the weir is approximately 280 metres in length and the eye section appears to have undergone at least three stages of construction. The builders appear to have utilised higher ground to the north and west of the weir to create a complete enclosure at low tide.

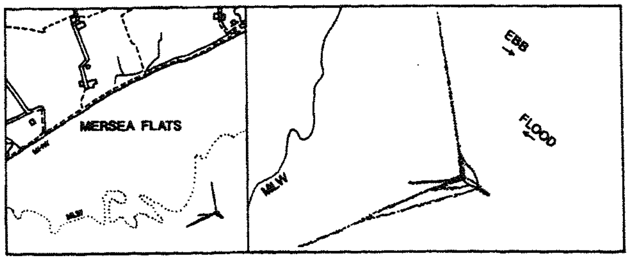

Fig. 7.25: Sketch representation of the East Mersea fish weir, compiled from oblique aerial photographic records by Strachan (1997). This is the least accessible of the Blackwater sites, located 1.5km offshore and at the level of the very lowest predictable tides. The site has only been seen once from the air and has never been visited; consequently, knowledge of the site is minimal.

The site is backed by a bank of sediment, which effectively isolates the catchment area from the sea during the period when tidal levels lie beneath it. The area between this bank and the shore of Mersea Island comprises extremely soft mud (Hall *pers. comm.*), which makes pedestrian access to the site extremely difficult. It was considered possible that the location of weirs within the estuary might be related to the distribution of compacted surfaces, subsequently buried by estuarine sedimentation. Chirp data acquired from the site[1] was examined for information upon the substrate immediately beneath each weir section, utilising positioning data from the 500 kHz survey. A clear erosion surface can be identified throughout the area, at a depth of c. 3-8 metres below the seabed. The banks behind the East Mersea fish weir are formed from material overlying this erosion surface. The location of the weir itself appears incidental to the underlying sediment; in some locations the weir lies upon the exposed erosion surface, whilst elsewhere the thickness of overburden is too great for the stakes to have penetrated.

[1] Details of the Chirp processing algorithms employed are contained in Appendix I.

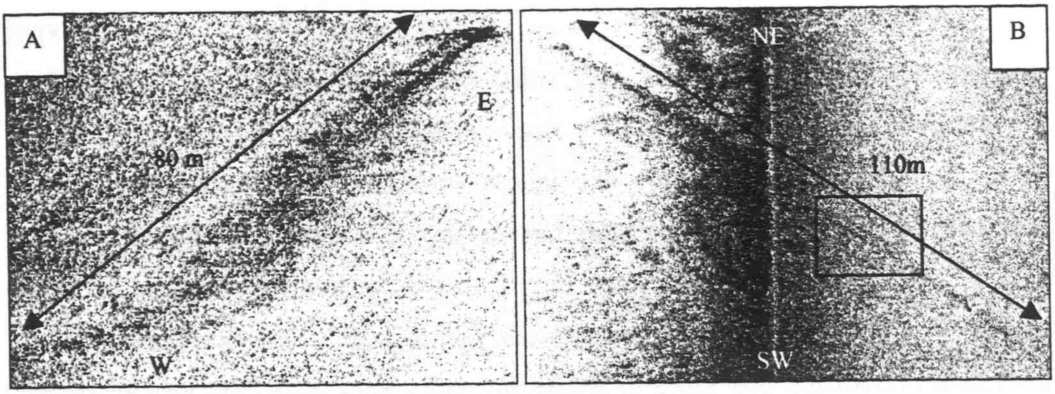

Fig. 7.26: Side scan sonographs of sections of the East Mersea fishing structure. The necessity of multiple-orientation overlapping survey lines is illustrated in this image of the trap eye (A), acquired on a NE - SW survey grid. The eye of the weir and a section of its southern limb are clearly imaged, but the northern limb appears absent. This limb was subsequently imaged with an east-west orientated survey grid (B). The typical signature of degraded wooden fish weirs imaged in extremely shallow water is demonstrated here (B); this is a section of the northern limb of the East Mersea structure, located approximately 100m to the north of the eye. In places the anomaly can be resolved into two separate linear elements (boxed), corresponding to multiple phases of construction.

Prior to side scan survey, the structure of this site was perceived as comprising a "V" shaped weir, which had undergone several stages of rebuilding, characterised by sub-parallel lines of stakes. Side scan sonographs contain clear linear anomalies in within the main weir enclosure (fig. 7.27), which are not visible in the 1993 aerial photographs. These anomalies comprise three sets of linear features of 150m maximum identified length. One set appears to represent a total 200m northwards continuation of the eastern limb of this weir, whilst the remaining two groups lie on the landward limits of the main enclosure and appear to lie a small distance (c. 10-50m) seawards of the landward, raised area of soft mud. Non-detection on aerial photography suggests that the source of these anomalies is a structure of low protuberance, or possibly a textural change in seabed properties. Observations from elsewhere in the estuary (e.g. the Nass, Collins Creek and Sales Point: this chapter) suggest that pathways were constructed across the tidal flats to facilitate access to the weirs. It is logical to expect that these pathways were constructed along the shortest path available, across areas exhibiting rapid drainage, to enable optimal use of available tidal access time to the weir. The fastest drying areas should lie on top of the raised banks to the north and east of the site, yet the anomalies observed lie mainly to seaward of this bank. If these anomalies are representative of access pathways, there should be a strong argument against construction on the raised areas. Four suggested hypotheses are:

1) The mud banks were considerably softer than the lower-lying areas of the weir catchment and thus required thicker, more elaborate structures to facilitate safe crossing. Construction of walkways linking the open ends of the weir along the fastest-draining area of the weir catchment facilitated a single landward connection, requiring less materials and construction time.

2) Currents associated with drainage across tidal flats can be strong. Walkways constructed on the banks were more vulnerable to scour and destruction than those located lower on the flats, so required more maintenance.

3) These anomalies do not represent walkways, but result from subjective interpretation in an area containing numerous linear anomalies. Data from this region contains very few linear anomalies and is generally low in backscatter; it is the author's belief that the majority of these anomalies represent structures of anthropogenic origin.

4) It is possible that additional walkways exist on the banks, but have been buried by mobile sediment.

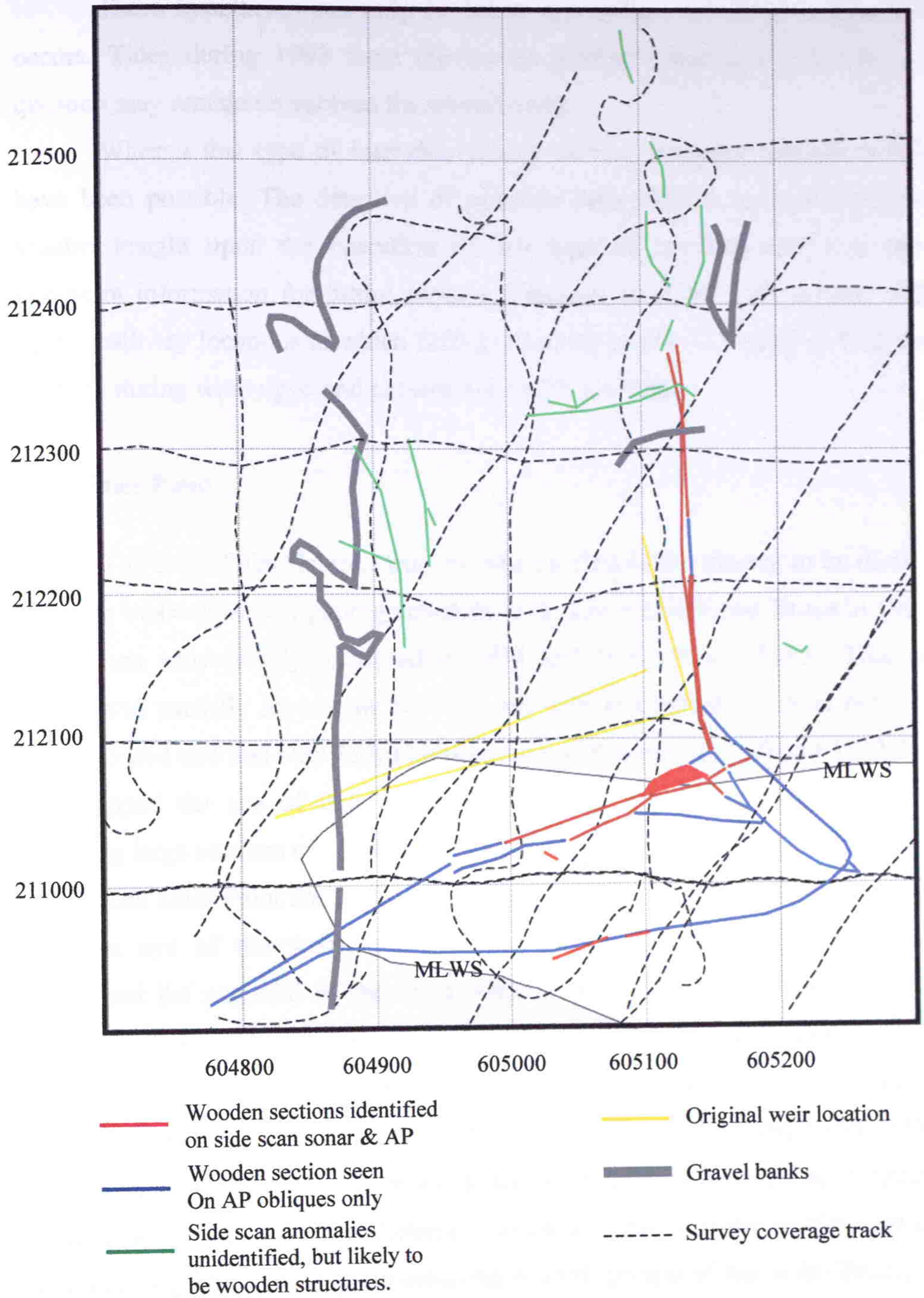

Fig. 7.27: Isometric plot from side scan and aerial photographic evidence of the East Mersea Flats fish weir. Because of the limited SMR, this site was surveyed with three different 500 kHz side scan sonar orientations and an overlapping grid of Chirp / 100 kHz side scan coverage. The weir was found to be much larger than initial estimates, appearing to utilise high ground to the north and west to form a complete enclosure during low tide.

These hypotheses can only be tested if a suitable predictable tidal window occurs. Tides during 1993 were the lowest predicted during the C20th, so this question may remain unresolved for several years.

Without this type of inter-disciplinary survey, mapping this site would not have been possible. The detection of possible walkways in unexpected areas has yielded insight upon the operation of this type of structure and also provides important information for future surveys. Findings from this site suggest different access pathway locations in which field archaeologists should expect to find material dropped during work upon and passage across the mudflats.

7.17: Sales Point

The Sales Point fishing structure was the first in the estuary to be discovered. This site was extensively photographed from the ground by Kevin Bruce in 1967 (fig. 7.28), then subsequently measured in 1974 and 1993 (Bruce, 1993). This weir is visible and partially accessible from the sea wall at Bradwell on Sea, but is rarely fully exposed and was only fully photographed on the very low tides of 1992. Erosion has stripped the site of large areas of overlying sedimentary cover since 1967, revealing large sections of previously hidden wooden structure (Bruce, 1993).

The Sales Point fish weir is visible on aerial obliques as a rectilinear structure, with the eye of the weir located at the north-eastern corner. This orientation maximised the potential of the local, shore-parallel, ebb tidal currents. Additional sections of this weir have been observed beyond the trap closure and within the main enclosed area (fig. 7.29). Bruce (1993) also describes basketry and possible buried linear features to the south of the site. Baskets located close to and south of the trap closure were approximately 1m in length and 30cm wide at the opening. Fragments of hurdle (wattling panels) are scattered across the mud flats and are visible from the sea wall; hurdling is particularly concentrated toward the eye of the weir (Bruce, 1993). The southern, seaward and northern walls are constructed from silver birch posts approximately 23cm (*9 inches*) in circumference, protruding approximately 23cm from the seabed. Other elements of the structure, such as the landward wall and some of the satellite walls are less substantial. These differences have been inferred to represent multiple periods of use; it has been suggested that the lesser sections significantly post-date the main weir structure. Extensive terrestrial survey has revealed the presence of scattered Roman pottery around the southern walls. Roman bricks also appear to have been incorporated into the main trap closure, although the purpose of their use is unclear.

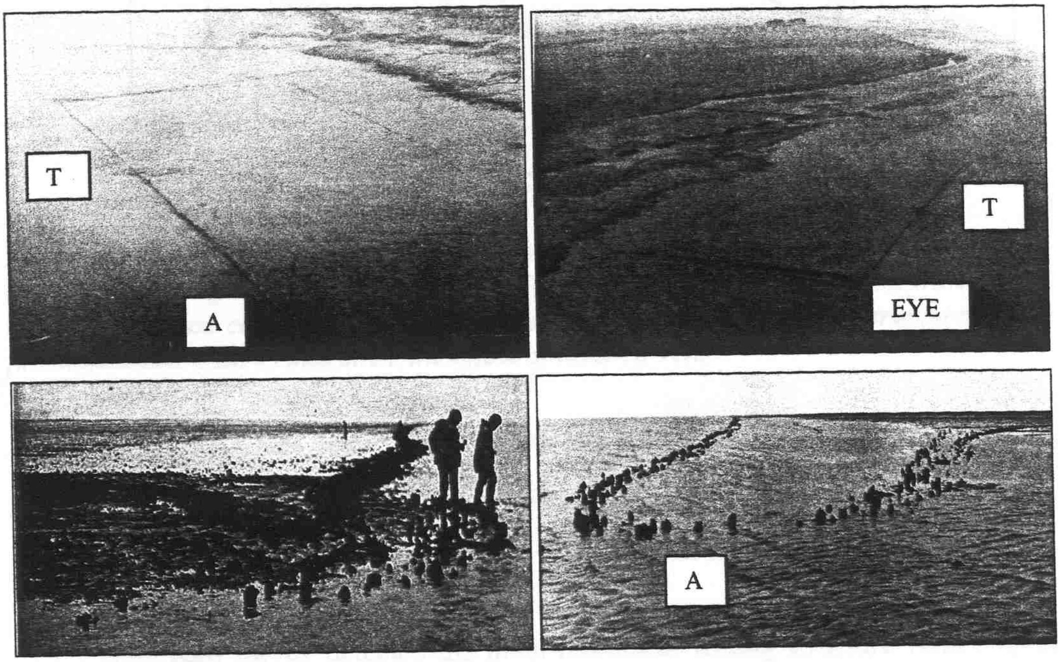

Fig. 7.28: Wooden fishing weir at Sales Point, Blackwater estuary. This weir appears approximately rectilinear in shape, with a main "eye" at the south-east corner (top), and a secondary curve at the northern seaward corner, which Bruce (1993) considers to represent a later stage of construction. The main, seaward wall is approximately 350m in length. Successive rebuilding is evidenced by cross-cutting and structurally redundant sections of the weir. Sonographs of the site can differentiate between the narrow, "clean" seaward wall and the neighbouring southern walls, which enclose a slightly raised area of shell- and hurdle-strewn material (bottom). Post diameter (for scale) is approximately 23cm.

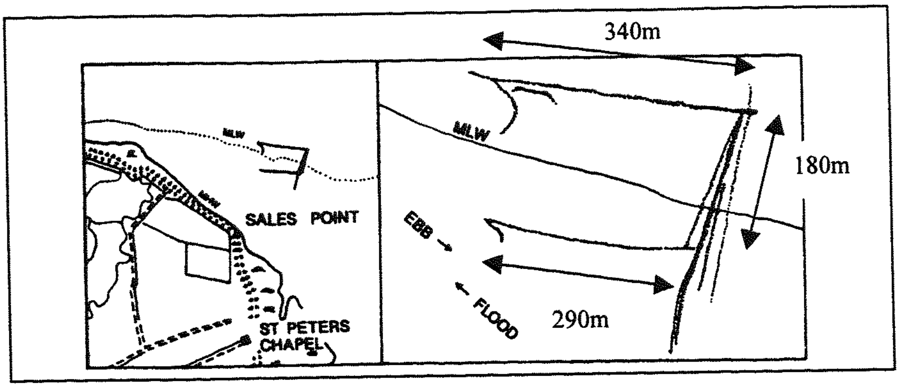

Fig. 7.29: Sketch plan of the Sales Point wooden fishing weir compiled from aerial oblique photography by Strachan (1997). The weir is rectilinear in shape, with an eye at the north-east corner, providing a good example of how fishing structures were positioned and built to maximise the effect of tidal currents.

A 500 kHz side scan survey of the site was conducted on a simple set of parallel coverage lines at 100 metres spacing (fig. 7.15). Total ship track length was 8km, which included repeated lines, yielded 0.6km^2 of areal coverage and was completed within 90 minutes.

Side scan survey detected the main rectilinear fishing structure visible upon photographs contained within the SMR (fig.7.28, 7.30), confirming the previous aerially determined position and correcting for distortion arising from the use of oblique photography. A large number of additional linear anomalies were also detected. The known major wooden structural elements are clearly identifiable on sonographs of the site (fig. 7.30). Measurements and observations recorded between 1967 and 1993 by Kevin Bruce (1993) and subsequently by Essex County Council (Strachan, *pers. comm.*) provide excellent ground truth information at this locality. The apparently excessive width of anomalies representing the southern and seaward limbs (c. 4-10m) is explained by Bruce (1993), who describes these lineaments as being constructed of sub-parallel lines of wooden posts enclosing slightly raised areas of seabed, strewn with hurdling, shells and other debris (fig. 7.28).

An isometric plot of the Sales Point weir structure has been produced from the aerial and side scan data (fig. 7.31). A large number of additional linear sections located both outside and within the main structural enclosure have been detected as a result of this survey (fig. 7.30). Several of these represent walls described by Bruce (1993), but their seaward extent is greater than previously suspected. A large, broad anomaly, which crudely bisects the seaward limb (location T, fig. 7.28 & 7.30) was previously not carefully inspected, and considered natural, but discovery of apparent additional structures in this area now suggest a possible man-made origin. Many of the unexplained anomalies located within the enclosure exhibit a clear inter-relationship with the known weir structure; often these anomalies terminate against the main walls of the weir (fig. 7.31). Examination of oblique aerial coverage within the SMR indicated that some of these linear anomalies are faintly visible through a shallow covering of water. No structures likely to cause these anomalies were reported during field investigations of 1993 and 1996, but erosion at this site is proceeding rapidly and new material is exposed every winter (Bruce, pers, comm.). The manner in which these parallel anomalies terminate against the weir is suggestive of a man-made origin. The purpose of their construction is uncertain, however, and four hypotheses merit consideration:

1) The anomalies represent walkways constructed for access to the weir walls and eye for extraction of the catch.

2) The anomalies represent sections used to internally subdivide the weir such that several different eyes would be created. A number of parties might then be able to operate separate fisheries within a single main structure.

3) The anomalies pre-date the main structure, forming successive generations of complex structures similar to those observed off Whitstable (fig. 6.6). The most prominent structure thus represents the oldest weir, superimposed over structures which have decayed to leave only minor traces. Justification for this hypothesis derives from two points: some of the newly discovered anomalies appear to form V shaped closures (fig. 7.31) and many of them extend into the subtidal, beyond the recorded limits of the weir. Rising RSL and records of Roman occupation at Orthona, Bradwell-on-Sea (Bruce, 1993), indicate the potential for earlier fishing structures at this site than established.

4) The anomalies represent natural features: this is unlikely, in the author's opinion, given the linear nature, regular angles of intersection and apparent interconnectivity of the anomalies.

The Sales Point fish weir is relatively frequently exposed, and is undergoing rapid seasonal storm erosion. Evidence from side scan sonar surveying during 1998 indicates that substantial further structure has been uncovered since the last dedicated field examination (1996), both within the weir, and beyond it, in the subtidal zone.

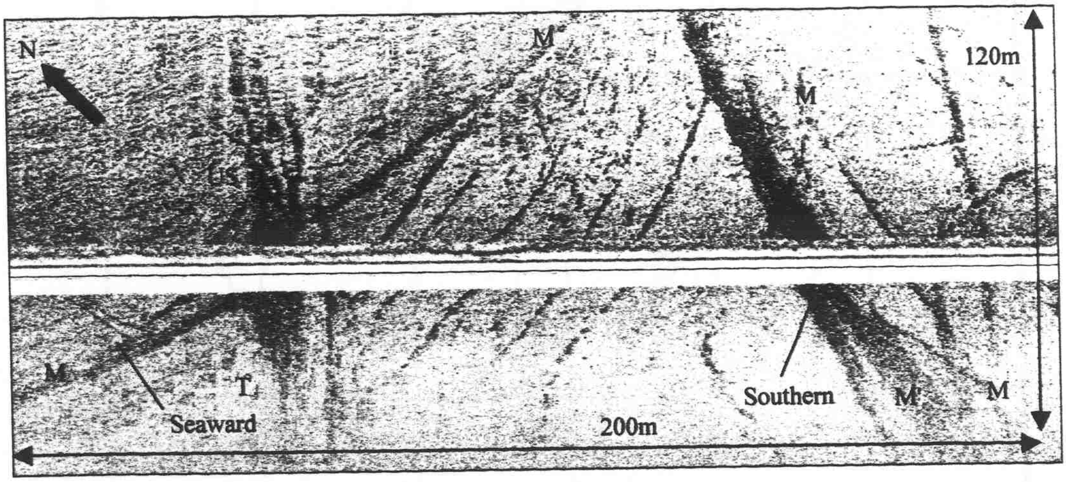

Fig. 7.30: Side scan sonograph of an area of the Sales Point site, close to the eye of the weir. Notation is that developed by Bruce (1993). The main limbs of the wooden weir are easily identified (M, M'), as is an area of upstanding seabed (US) which cuts the seaward limb of the weir and is clearly visible on aerial obliques. The southern main limb (M') is a vague area of strong reflection up to 10 metres in width. Curves in lineations around the centre line are a result of slant distortion in the side scan data. Visitors to the site describe parallel lines of posts enclosing a slightly raised area strewn with hurdling, shells and fish bones (fig. 7.29); this explains the indistinct anomalies observed at this locality, in contrast to the sharp images obtained elsewhere (e.g. Pewet Island). There are a large number of additional linear anomalies upon this site, all of which appear geometrically related to the main weir structure.

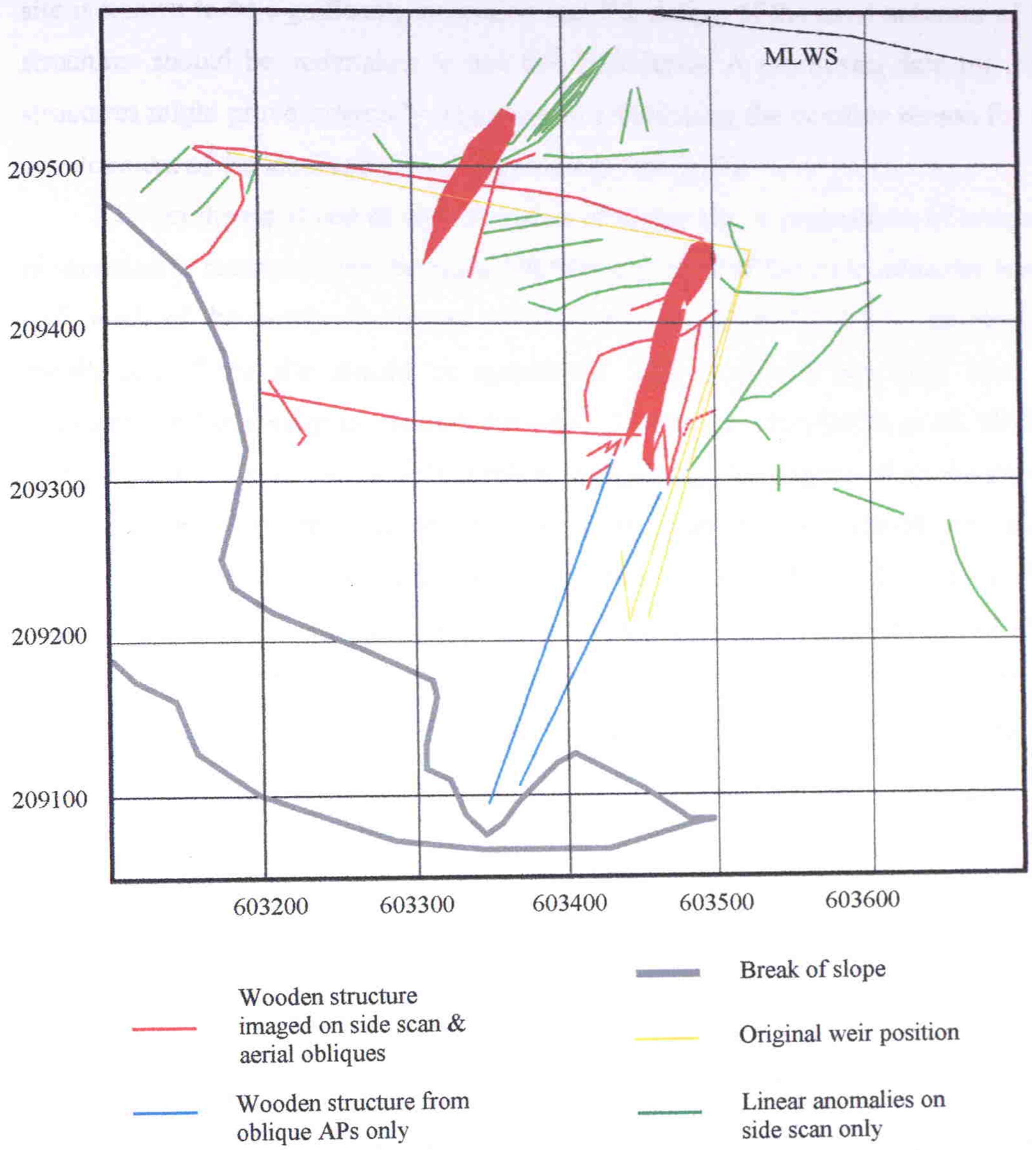

Fig. 7.31: Isometric plot of the Sales Point fishing weir. This site contains a large number of additional linear anomalies, which are largely unexplained. Some of these features appear contiguous with known elements within the basic rectilinear weir structure, whilst others are not recognised from photographic records and may have been recently eroded.

Side scan survey of the Sales Point fishing structure, supported by ground truth and aerial information from the intertidal zone, has facilitated accurate mapping of the known structure at this site and has increased the total amount of known wooden structure by 50-70%. This newly discovered material is highly significant, as it suggests that remnants of a possible earlier fishing industry may be located within the intertidal zone, extending into the subtidal. Erosion of overlying sediment at this site is known to be significant; inspection and ^{14}C dating of the most seaward of the structures should be undertaken to test this hypothesis. A pre-Saxon date for these structures might prove extremely important in establishing the possible reason for the development of the local coastal fishing industry (see 7.19).

Given the rapid rate of erosion observed at this site, a programme of temporal observation is recommended. Because full tidal exposure of the main structure is rare and much of the newly discovered material may lie beyond MLWS, geophysical monitoring of the site should be considered. This technique has been used by Southampton University to monitor the Invincible wreck site (Quinn *et al*, 1998a), and provides a rapid and reliable method for gauging the degree of exposure and destruction resulting from storm activity. In addition, the site should be visited whenever partially exposed during spells of safe meteorological, tidal and daylight conditions. Although the resource at site is undergoing rapid depletion, regular field inspection may yield large amounts of information on the operation of early coastal fishing weirs, if a policy of careful and regular observation is included within the Blackwater Estuary Management Plan.

7.18: Collins Creeks

This site, centred upon the Upper and Lower Collins Creeks (fig. 7.15) is the largest recognised wooden fish weir complex in Essex, and one of the most extensive in Britain. The entire site measures approximately 3km x 1km and is located on an upstanding area of mud flat approximately 1km from either shore of the estuary, bounded respectively to east and west by Thirstlet and Goldhanger Creeks. Inaccessibility to pedestrian visits is compounded by the soft-banked Upper and Lower Collins Creeks, which internally subdivide the complex. The topography of the site is often extremely uneven; the surface consists of mud mounds incised by numerous drainage channels and crossed by ridges of coarser sediment (fig. 7.32). To the east, tidal erosion has created a spit of coarser shell and gravel material, whilst the northern areas consist of featureless soft sediment.

By comparison to the Mersea weirs, the Collins is relatively well exposed: on the lowest spring tides of any year, the highest part of the site is exposed for 3.75 hours, although the main areas are exposed for just 2 hours and marginal areas may not be exposed.

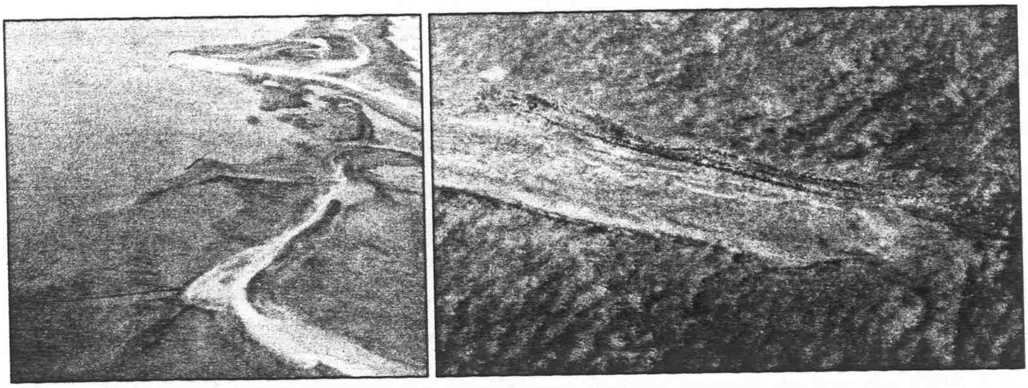

Fig. 7.32: Aerial oblique photographs of the southern edge of the Collins Creeks complex: no scale available. There is no simple geometric shape to describe this site; the topography consists of steep mud banks, spits, and silt and shell ridges, upon which are located numerous lines of upright posts and sections of hurdle from walkways and weir walls. It is estimated that the complex contains over 20 000 stakes.

The Collins Creeks complex was discovered by Ron Hall during 1989 (Hall, 1997). Subsequently, the site has become the focus for archaeological investigation within the Blackwater Estuary. This interest has been sustained by three factors: the exceptional size of the site, the difficulties of mapping such a large, complex and inaccessible structure, and the site's proven vulnerability to wave damage. This vulnerability arises from frequent exposure to the prevailing south-westerly winds, which at low tides cause large waves to break upon the eastern end of the complex, where active erosion is rapidly and visibly destroying the site (Hall, 1997).

Analysis of stakes from three sites within the complex has shown that oak is the predominant building material. At the only site containing non-oak timbers, the posts bore injury scars, suggesting that they were cut by different people or at different times (Groves, 1993). Dendrochronological analysis of material from the site has not been possible due to insufficient growth rings within the timbers removed for analysis. ^{14}C dating of a small number of stakes yielded five dates ranging between 640 and 957 AD[2]. Whilst no excavation of the site has been conducted, artefacts seen to be eroding from the sediment include a possible Roman sherd and a C16th bowl (Hall, 1997).

Attempts to map this complex by aerial and terrestrial approaches have encountered variable success. The SMR collection of oblique and vertical photography is of limited use, as many of the obliques pre-date the advent of personal GPS sets, whilst the vertical coverage was acquired from too great an altitude. An

[2] These are the outer error limits of σ^1 dates.

accurate map of the site (fig. 7.33) was compiled by land surveyors from the University of East London, who constructed a differential GPS survey by the "stop and go" field walking method during a succession of low tides in February and March of 1993 (Dare, 1994). This method was found to be relatively fast, although parts of the complex remained inaccessible. A number of stake lines were observed running into marginal subtidal areas and creeks within the complex; this prompted Dare to speculate that a large expanse of the site might lie within the subtidal zone. Unexploded ordnance provided a significant further hazard during the GPS survey, being virtually indistinguishable from weir components and requiring the attention of a military bomb disposal unit.

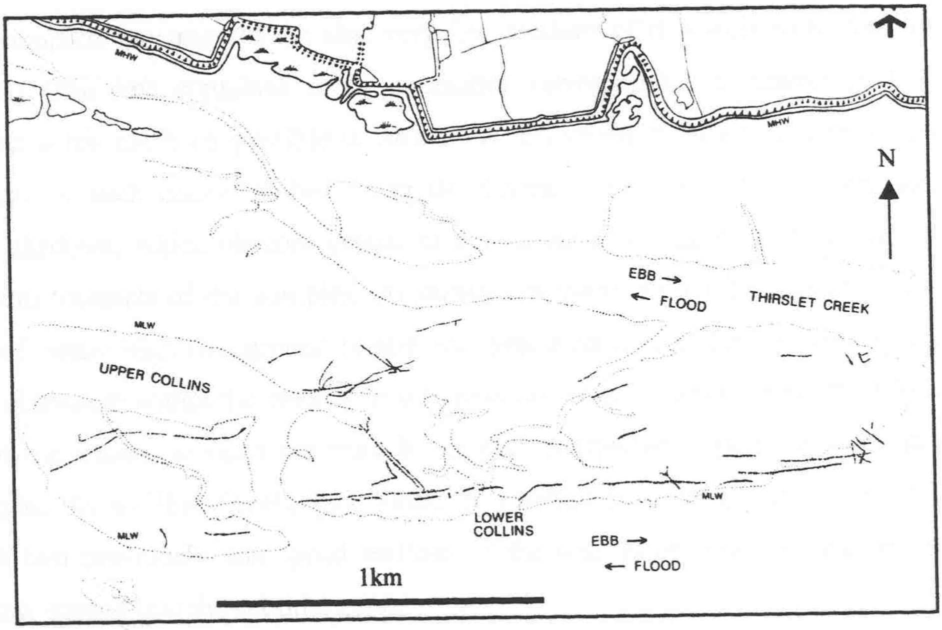

Fig. 7.33: Sketch of the Collins Creek wooden fish weir structures, drawn from aerial oblique and vertical photography (Strachan, 1997) and supported by terrestrially deployed differential GPS mapping. The DGPS survey was completed by the University of East London during Spring 1993, as described by Dare (1994).

Unlike the Mersea Island structures described in this chapter, the Collins complex does not consist of easily definable geometric shapes. Although some lineations converge to form a closure, many sections of the weir appear to lie atop ridges of firmer sandy silt and shells, parallel to the marginal break of slope. A limited auger survey conducted on the southernmost east-west post line showed that the surrounding ridge stood within soft mud up to 3.5 metres deep (Hall, *in progress*). In-situ discoveries indicate that these areas of soft sediment were crossed by secure walkways, constructed by driving vertical oak stakes through panels of wattling.

Geophysical survey of the Collins Creeks site was limited to a single set of parallel 500 kHz side scan survey lines, each approximately 2.75km in length (fig. 7.15), with a total survey length of c. 30km. The extent of the survey was restricted by tidal considerations; water flows rapidly east-west across this area, preventing acquisition of accurate north-south survey lines across the main complex, and adversely increasing survey speed when moving with the current. There are several navigational hazards around the site, in addition to the grounding dangers posed by steep banks and unexploded ordnance.

The results of this survey lack the detail observed elsewhere in the estuary. Despite complete coverage of the site, very few sections of fish weir were detected (fig. 7.35). The data contained many anomalies corresponding to gravel or shell ridges, but it has not been possible to isolate the reflections from wooden structures from those of such coarse seabed materials. Furthermore, these ridges often cast acoustic shadows, which obscure details in the far field. Strong currents prevented north-south transects of the complex, so survey coverage is poor by comparison to other sites where high background scatter was problematic (e.g. East Mersea Flats). At sites elsewhere within the estuary, it was possible to detect approximately 60% to 100% of the known wooden structure by careful interpretation of multi-orientated sonographs. At Collins Creek, this figure is estimated as being less than 10%, although two previously unmapped sections of the weir have been located, one of which may extend into the subtidal zone.

The first of the new sections comprises a 150m long linear anomaly on the northern banks of the Collins (GR 594200 207500 - fig. 7.). This anomaly maps continuously onto the end of a wooden structure of similar length and orientation, mapped by the University of East London DGPS survey (Dare, 1994). The local bathymetry is relatively constant in this area, so it appears that the section may have been overlooked during this survey.

The second newly identified likely wooden structure consists of two short linear sections, 50-70m in length, located on opposite sides of a creek on the southern edge of the complex (GR 594550 207100). The position of these sections suggests that they form part of a much larger wooden structure, identified as tracking discontinuously for 2.5km across the southern edge of the complex. Creek banks on the Collins are extremely soft; the position of these anomalies suggests that they may lie in an inaccessible, possibly subtidal location, which was not investigated during previous terrestrial surveys.

The survey of Collins Creeks demonstrates the limitations placed upon side scan sonar surveys by difficult environments, in terms of currents and seabed topography and texture. It also exemplifies the benefits of a fully inter-disciplinary approach to inter-tidal archaeological survey, as the inability to detect large expanses of the fishing structure using side scan sonar was compensated for by success with other techniques. Future Management Plans for intertidal areas which make provision for all three techniques in the initial survey stages are therefore likely to be more effective and less likely to overlook structures in the intertidal or subtidal zone.

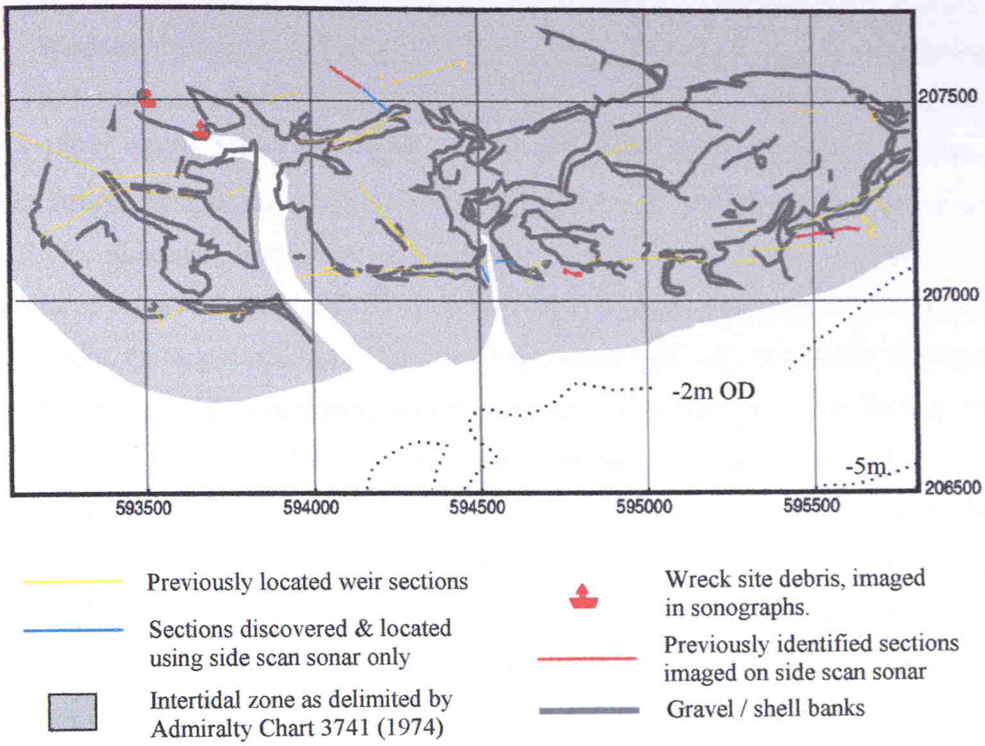

Fig. 7.35: Integrated plot of Collins Creek fish weir location, incorporating results from the 1998 side scan survey, ECC terrestrial survey, University of East London's DGPS survey (Dare, 1994) and bathymetric data from Admiralty Chart 3741 (1974). Despite the strong record of previous work at this site, very little wooden structure was unequivocally identifiable from the sonographs. This result serves as a reminder that despite the great advantages offered by intertidal geophysical survey and demonstrated elsewhere within this chapter, careful consideration of the site environment is essential prior to commissioning a full survey.

N.B. The delimited intertidal zone at this site appears generously over-drawn. This may be a result of subsequent erosion, or more probably, a deliberate safety strategy on the part of HM Hydrographer, as the area is popular with pleasure boaters.

7.19: Pewet Island

Wooden structures on Pewet Island were first discovered from the air during early 1993 and immediately visited, photographed and described by Kevin Bruce (Bruce 1993, Wallis 1994) (fig. 7.35). The SMR records only the presence of two distinct structures approximately 600 metres apart, to the north-west of the island (Fig. 7.36), although descriptions from the ground imply a single structure. The foreshore of Pewet Island slopes more steeply than at most sites within the estuary; consequently, the upper reaches of the known weirs are relatively frequently exposed, whilst the full subtidal extent of these structures has never been recorded. During the best, recorded exposure (1993), it was impossible to view the entire structure; a 1906 waterways report discovered by Bruce (1993) indicates that even at this time, only the upper ends of the weir were visible, entering deeper water (fig. 7.36). Considering that this site is sheltered from swell, yet remained submerged to at least 0.3m whilst its contemporaries were fully exposed, it is reasonable to suggest that this may be the oldest known major coastal fishing structure in the Blackwater Estuary.

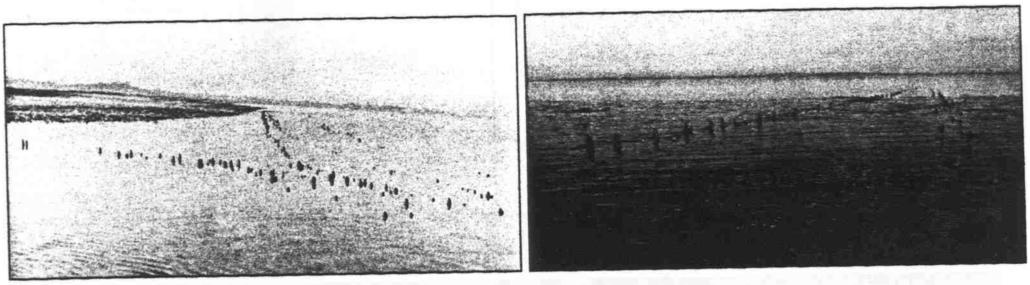

Fig. 7.35: Wooden fishing structures on Pewet Island, Blackwater Estuary. The submerged section of this weir has not been exposed since the site was discovered, even on the low tides of March 1993. These photographs were taken on one of the lowest predicted tides of the century, indicating the subtidal nature of much of the site. Scale is problematic, but the post lines in the right-hand picture are c.80 metres in length. The Pewet Island structures appear less cluttered and diffuse than their contemporaries, producing clearer sonographs, as demonstrated in the following figure.

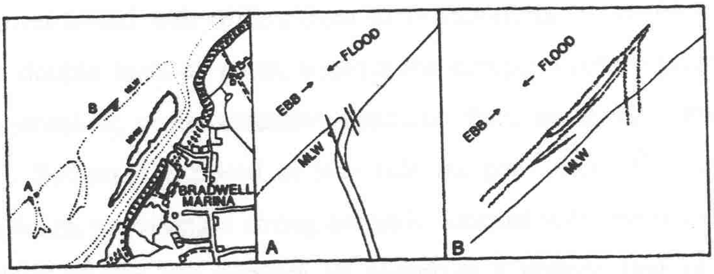

Fig. 7.36: Sketch map of structures recorded on the north-west shore of Pewet Island, Blackwater Estuary. This map was compiled by Strachan (1997), from oblique aerial and terrestrial photography, plus information from low-tide field visits, but does not consider the observations of Bruce (1993).

Geophysical survey of this site comprised three parallel 500 kHz side scan lines, approximately 2km in length, at a separation of 100 metres, plus a single short Chirp line (fig. 7.16). Sonograph clarity at this site was excellent and occasionally sufficient to enable the resolution of individual posts within the weir (Fig. 7.37).

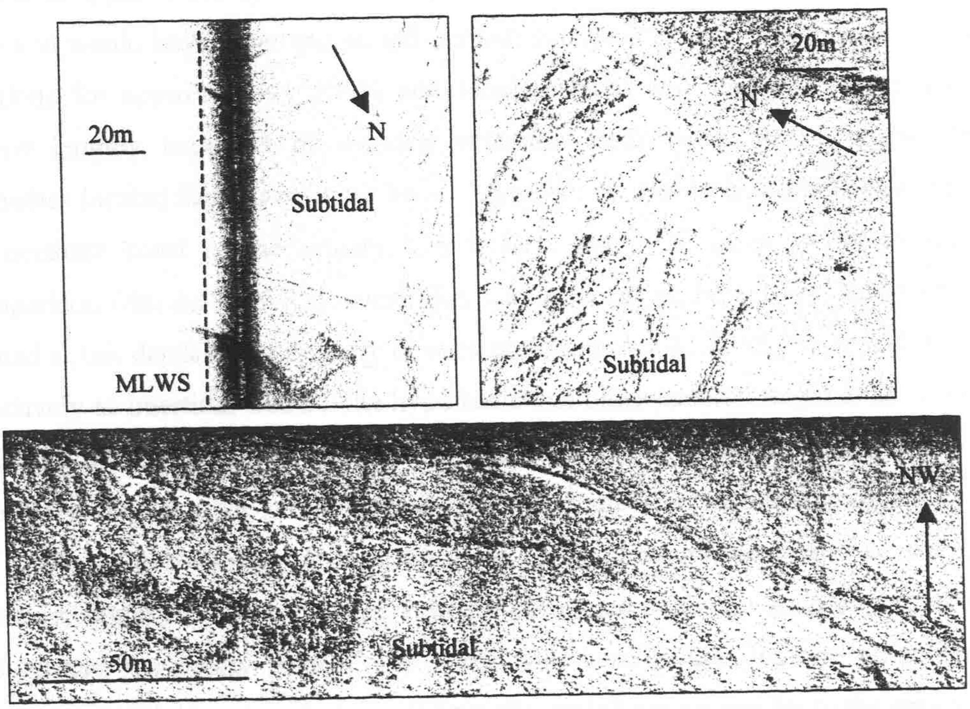

Fig. 7.37: Sonographs from Pewet Island containing clear evidence that the majority of this site lies within the subtidal, forming a major continuous complex at least 1.5km in shore-parallel length and 200 metres in width. Weir sections imaged within the intertidal zone are observed to continue for over 100m into the subtidal (top left), where the lines close to form traps (top right), often abutting against major sections of shore-parallel structure (bottom), believed to link all of the known structures into a single complex. These images correlate well with the general structure described by Bruce (1993), who was unable to view the site in its entirety.

The Pewet Island weir differs from its contemporaries, as the walls comprise only single or double lines of posts, without the complications typically created by multiple reconstruction, or the extensive hurdling observed at Sales Point (fig. 7.36) (Bruce, 1993). Sediment exposed at low tide suggests that soft, featureless mud surrounds the weirs, providing a strong acoustic contrast with the wooden posts. The general structure of the site appears to comprise a double line of posts, which approximately parallel, but lie 0.5m or more below, the MLWS isobath. These lines are approximately 1500m in length, and are sporadically inter-linked by sub-parallel and steeply crosscutting, shorter lines, which may have supported individual trap closures at intermediate points along the weir. All of these shorter sections are orientated such that they would exploit currents created by the ebb tide (fig. 7.36).

The weir appears to close at GR 599080,208500; its true westerly extent is difficult to establish, as the coast-parallel lines disappear into deep water and anomalies appear more broken. The majority of this site is located within the subtidal zone and would have gone undetected without side scan survey, which has provided locations for approximately 200% additional material and supports suggestion of further lengthy expanses of wooden structure. Bathymetric data suggests that anomalies located furthest offshore lie at -1.5m OD; considerably lower than weirs on the northern coast of the estuary, which have been ^{14}C dated to Saxon times. Comparison with the local RSL curve (fig. 7.2) supports the suggestion that structures located at this depth might be early or even pre-Saxon in age, if they were to function effectively as intertidal weirs[3]. The hypothesis that older material might exist at Sales Point can therefore be projected more confidently for Pewet Island; the proximity of these sites relative to the Mersea Island and Collins sites may also be significant.

There is a substantial terrestrial and aerial photographic record of the site, however, much of this cannot be reliably correlated with the sonographs, as the photographs are poorly located[4]. In places, side scan images indicate complicated structures containing several crosscutting walls, which appear similar to the structures photographed during 1993 and demonstrate the capability of this technique to resolve complex targets, given suitable acoustic conditions. Precise location of such hydrodynamic obstacles may provide suitable locations for future diver investigation;

[3] Changes in tidal range during the last two millennia have not yet been accurately determined, but simple comparison of site altitude justifies further investigation of this hypothesis.
[4] Most of these pictures pre-date the use of GPS for photographic positioning.

these junctions may act as traps for anthropogenic material discarded across the site during its operational life.

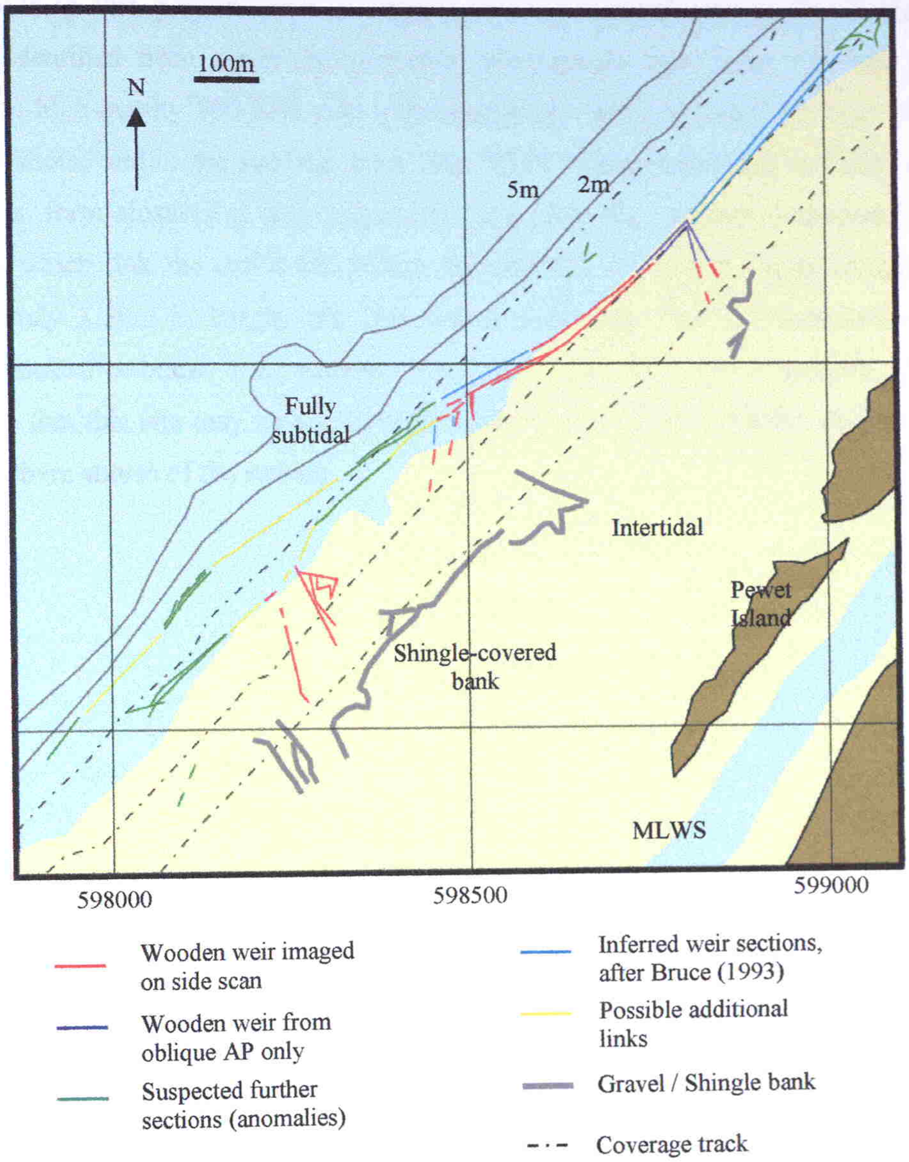

Fig. 7.38: Isometric plot of the Pewet Island wooden fishing structure site, indicating the probable true extent of this structure within the subtidal zone. The use of intertidal geophysical survey at this site has resulted in the location of extensive linear anomalies, which lie within the subtidal zone and map exactly onto structures observed extending outwards from the intertidal. This alters the perceived structure of this site, from a collection of individual post lines to a single complex fish weir comprising numerous interlocking arms and closures, located mainly within the subtidal zone. The weir appears to terminate in a 'V' at the far north-east of the site, but the true south-westerly extent is of the weir is less unequivocal, as scattered anomalies persist within the subtidal zone for several hundred metres.

Pewet Island is the best demonstration of how a shallow-water marine geophysical survey can contribute to the "seamless" inter-disciplinary methodology, to arise during this project. Isolated, poorly located sections of wooden fishing structure identified from aerial and terrestrial photographs have been matched to features on high-quality 500 kHz side scan sonographs and continued for over 100 metres offshore, within the subtidal zone (fig. 7.37). These individual sections are observed to form closures at their extremities and often abut against shore-parallel structures which link the entire site within the subtidal, forming a single complex approximately 1.5km in length and 200 metres wide (fig. 7.38). Comparison of precisely-located subtidal weir sections with the local RSL curve supports the hypothesis that this site may be significantly older than contemporaneous structures on the northern shores of the estuary.

7.20: The Archaeological Significance of the Blackwater Estuary Fish Weir Discoveries

Evidence from inter-disciplinary survey within the Blackwater Estuary has indicated the true extent and complexity of the wooden fishing structures of this area. From the scale of the structures discovered, the ancient fishing industry of Essex would appear to have been an important element in local and perhaps regional food supply and consumption. AMS ^{14}C dating shows that the known wooden fish weirs of the Blackwater Estuary are probably middle Saxon in origin (fig. 7.3), whilst the earliest Saxon weir in the estuary is currently dated to c. 650 AD. Attempting to place the recent discoveries into historical context requires a short review of the development of Anglo-Saxon Essex. The historical record at this time is poor, and we know relatively little about the social structure and lifestyle of the Essex populace at this time. As recently as 1994, assessments of Anglo-Saxon subsistence on the shores of the Blackwater were based only upon evidence and records relating to exploitation of the land (Murphy, 1994), with little or no reference to exploitation of the marine resource. It now appears that models of trade and subsistence in Anglo-Saxon Essex may be flawed to a degree, by lack of this information.

It is important to acknowledge that a mid-Saxon date for origin for the construction of the earliest weir is based upon a very limited number of AMS ^{14}C dates from randomly selected posts (Strachan 1997). Consequently, structures of greater age may remain unsampled, particularly within the subtidal zone at Pewet Island. The current hypothesis of an Anglo-Saxon (rather than Romano-British) origin for the Blackwater fisheries will only be proved if a more extensive dating program yields statistically sound evidence for the absence of older materials within the weirs.

Roman Britain was a society founded upon trade links between fortified towns, along well-constructed communication links. The Roman garrison effectively abandoned Britain in 407 AD, leaving a power vacuum in place of previous direct administration from Rome. Loss of direction led to a decline in communication, severing trade links and resulting in migration of the populace from the Roman towns into the villages, farms and hamlets of the countryside. This is thought to have been a gradual rather than immediate process, but may have occurred over a period of half a century, as decreasing demand for food and materials from the depleted urban populace led to a progressive decline in the planting and harvesting of crops (Todd, 1984). Towns did not revert to a significant role within the country until the C10th (Hunter Blair, 1977). The resultant dispersal of communities across the countryside resulted in a depleted archaeological and historical record; consequently, less is known about the communities of the C6th and C7th than those of Roman times.

The collapse of the transport infrastructure, which had supported urban and agricultural existence, was accompanied by the arrival of numerous Angles, Saxons and Jutes upon the East Coast of England. This was perhaps not an invasion as such, as the Romans had originally employed people of these northern European races as mercenaries to strengthen their depleted British garrisons. The new arrivals came to settle the fertile lands of Britain, but their migration often resulted in skirmishes between the newcomers and those who were already attempting to take control of the land (Hodges 1984, Todd 1984). The socially disruptive effects of this migration were initially felt in the south-east, during the early C5th, and as the new populace established itself and spread inland, this area would also have been at the forefront of subsequent developments in Anglo-Saxon civilisation.

As the demographic distribution decentralised, the populace reverted to subsistence agrarianism, living in small, dispersed communities in comparative social isolation. Anglo-Saxon society was principally agrarian and village-based. Specialists were rare: there were no labourers, no entrepreneurs and no bureaucrats (Hodges, 1984). Very little is known about the two centuries following the final Roman withdrawal, although the historical record improved during the late C7th. This improvement was triggered by the return of Christianity as a major religion, displacing the pagan beliefs of the post-Roman peoples and encouraging education and historical recording. Perhaps significantly, a Christian mission was established c. 600-620 AD on the site of the Roman fort of Orthona, near Bradwell-on-Sea, between the sites of Pewet Island and Sales Point (Laing & Laing, 1979). By the late C7th, improved trade, growing towns and the resumption of taxation upon a growing populace by newly ascendant rulers, would have exerted increased pressure upon the available rural resources (Arnold, 1997).

The causative factor behind the apparent appearance of large wooden fisheries in the Blackwater at this time has been the subject of some speculation (Strachan 1997), Bruce (*pers. comm.*). Three suggested reasons are taxation and urban growth, monastic enterprise, and simple subsistence requirements, none of which are mutually exclusive. The scale of the Blackwater Fisheries is striking; the Collins Creek complex is estimated to contain over 20 000 wooden uprights (Hall, *pers. comm.*), emplaced over a period of approximately 250 years. These would have required a major endeavour in coppicing, trimming, emplacement and maintenance, plus construction of hurdling for walkways, fencing and basketry. Estimation of the number of stakes and hurdling sections within the five further sites described in this chapter will require further field visits, but each site would must have represented a major undertaking. It seems likely that a substantial local workforce was present in the area during the C7th and possibly later; this is contradictory to modern views of dispersed, agrarian society in Anglo-Saxon Essex.

The Domesday Book of 1086 (*trans.* Morris, 1983) describes a number of "fisheries" within the Blackwater Estuary (fig. 7.40), at locations corresponding to the approximate areas of known fish weirs at Pewet Island, Sales Point, Mersea Island and the Nass, plus further fisheries off Osea Island and Lawling Creek. Concentrated aerial and marine reconnaissance of this site during the 1990's found no evidence of wooden structures within Lawling Creek, although upright timbers were observed on mud flats near Coopers Creek, 500m to the west (Bruce, 1993). This environment is comparable to that in which weirs have been discovered elsewhere within the estuary: a broad, flat area of mud flanked by drainage channels. Whether references in the Domesday Book correspond to the known wooden fishing structures is uncertain, as this source is often inconsistent in its description of sites related to fishing and does not differentiate between fishery types. AMS ^{14}C dating currently yields a sigma-2 value of 980 AD for the youngest upright sampled; a gap of over 100 years thus exists between dated material from the coastal fish weirs and the presence of fisheries recorded in the Domesday Book. There is therefore no record that the coastal fisheries were still active during the Domesday survey. The scale of these coastal fisheries is sufficient that a Domesday reference would be expected; further ^{14}C dating may produce later dates, which will support this link.

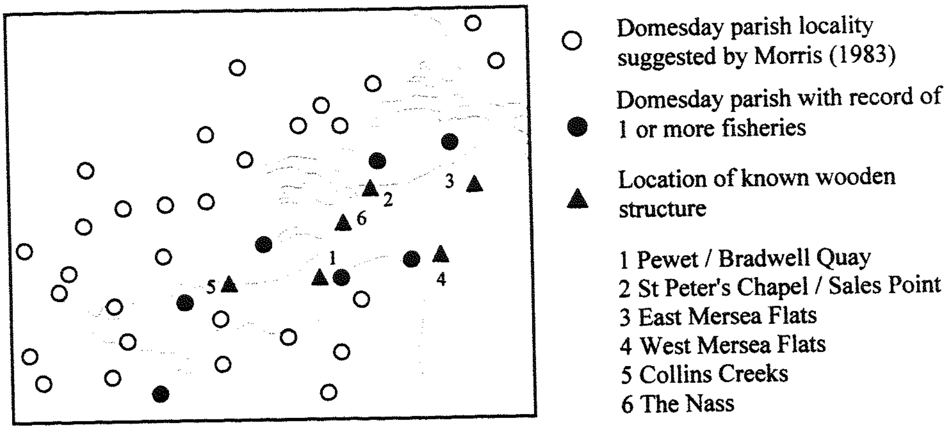

Fig. 7.39: Location of parishes of the Blackwater inferred from the Domesday Book (1086) by Morris (1983). Of 18 parishes appearing to have an estuarial boundary, seven are described as possessing "fisheries", although there is a recognised diversity in the nomenclature employed by the Domesday surveyors. Five of the sites correlate with the location of weirs described in this chapter (East & West Mersea, Pewet Island, Sales Point & The Nass). Allowing for land reclamation, it is possible that reference to a fishery at Osea Island might actually describe the Collins Creeks complex, whilst observations of tidally-exposed timbers at Coopers Creek may suggest a location for the only site lacking positive identification, off Lawling Creek.

One of the most important findings arising from this survey is the previously unsuspected scale of the coastal fishing sites, and the correspondingly increased perception of the importance of this industry. The appearance of a major coastal fishing industry at a time when the hinterland was undergoing pressure to support a growing and increasingly connected populace is an attractive explanation for the scale and apparent timing of the Blackwater fisheries. At present, the evidence supporting this scenario is encouraging, but insufficiently rigorous in investigative depth; this is unsurprising given the previously hidden nature of evidence concerning the scale of the Saxon fishing industry.

Determination of the scale, location and extent of these structures by a combination of side scan sonar and photography has demonstrated that the coastal fishing weir was of greater extent and possibly significantly older than previously suspected. The accurate maps resulting from both direct side scan imaging of submerged structures and correlation with less well positioned photographic evidence should be used as a frame for further site-specific investigation. Future investigation may place tighter limits upon the age of the weirs and might also identify periods of intensive repair and use. From the accurate site co-ordinates now available, it should be possible to commission a precisely targeted diving survey, aimed at testing the hypothesis that weirs on the southern coast of the Blackwater Estuary may significantly predate their northern, Saxon contemporaries. Precisely positioned diving may also be focused upon likely seabed traps, where material related to trap construction and maintenance may have collected.

The likely scale of the Saxon fishing industry would have strongly affected the local maritime cultural landscape of the Essex coast. A reappraisal of Saxon and Medieval texts containing information on local pasturing, dwellings, quays, roads, coppices and markets should be made, to investigate whether evidence for ancillary maritime activity have been misidentified as relating to local agriculture (Bruce, *pers. comm.*).

The reasons behind abandonment of stationary coastal fishing practices in Essex and the timing of this event have not been established. ^{14}C dates so far obtained from wooden uprights at Collins Creek, the Nass and Sales Point suggest early Medieval decline, but the small sample population is statistically unsound and further dating is required. If this date is proved approximately correct, then it is interesting that this method of fishing declined in the Blackwater when it was enjoying great popularity in the Severn Estuary Levels. Study of the isometric plots resulting from side scan survey shows that the fishing structure on the Nass exhibits closure at the highest altitude and thus may have operated at later dates than its contemporaries. This site should be targeted for further inspection; samples should be taken from posts located in the most shoreward phase of rebuilding.

In the previous chapter, a "taxonomy of fish weirs" was described, as proposed by Bannerman & Jones (1999). The main purpose of this classification system was to enable comparison with weirs from other regions. Results from the Blackwater Estuary and Strangford Lough suggest that weir design was governed by local factors such as currents, sea bed topography and availability of local materials. The fish weirs of Strangford Lough were constructed across drainage channels upon the tidal flats, but fall into a range of categories within the scheme proposed by Bannerman & Jones. East of Chapel Island, the stone weir surveyed was closest in type to Type 4 (Crescent), South Island is Type 3 (modified natural features), neighbouring stone weirs are of type 7 (V) and further east, the Greyabbey Bay weir is a further Type 4 crescent. It is apparent that the shape of these weirs was decided by the immediate environment and also, probably, by the accessibility of the site from the nearby settlement or monastery. In the Blackwater Estuary, the weirs are largely unclassifiable by this scheme; each has been built to fit the local environment in which it operated and most have undergone subsequent modification in response to rising sea levels. Whether location of these weirs was controlled by proximity to local villages or monasteries is not clear.

Attempts to classify coastal fish weirs in terms of simple shapes in order to facilitate comparison between regions are not productive, as demonstrated by the data acquired during this survey. If weirs from different regions are to be compared, then it may well be necessary to fully understand the physical, social and economic conditions prevailing during their construction, operation and eventual decline to abandonment. The question of whether fish weir technologies developed in a spontaneous, isolated manner, or by the gradual dispersal of information, will only be answerable when the development of the industry at each major locality across Britain is understood.

7.21: Review of Interdisciplinary Methodology

The use of high-resolution seismology within the intertidal zone has been demonstrated to be a rapid and effective method in the prospection and mapping of submerged archaeological structures. Given that shallow marine geophysical survey might now become an option to the wider sphere of inter- and subtidal archaeological investigation, it is necessary to assess the practical potential of the side scan system with a view to establishing a generic methodology. Experience has determined four important factors which require consideration when commissioning or designing an intertidal survey: seabed texture (sedimentary cover & topography), system resolution, grid orientation and sea conditions.

If the target is composed of units (rocks, posts, etc.) of similar dimension to the local seabed cover, then the probability of clear target resolution decreases, as the acoustic texture of the seabed across the target becomes uniform. Detection in this case becomes reliant upon anomalies created by the structural compactness and upstanding nature of the target, as seen at South Island, Strangford Lough and The Nass of the Blackwater Estuary. Sales Point provides a good example of this: in fig. 7.31 the general target area is easily distinguished from the surrounding soft sediments, but it is impossible to resolve wooden structure from wattling & entrapped shell material due to their textural similarity. The low angle of acoustic incidence typical of shallow water side scan deployment provides a significant advantage in the detection of upstanding targets, as the contrast in reflection strength can be extremely large.

System resolution was discussed in Chapter 2: the relationship between range and transverse resolution is highly significant in the detection of linear structures comprising spaced individual elements of 10-15cm diameter, as this dimension is close to the optimum range resolution of the 500 kHz system utilised (13cm). Transverse resolution increases to a minimum of 62cm at full operating range, but is equal to the range resolution for target offsets of approximately 14 metres. Resolution of individual posts within a structure is thus most likely within the most proximal 15-20m to port and starboard of the survey track. This implies that all of the targets imaged on sonographs within this volume must exhibit a degree of distortion. A clear example of simple offset-dependant distortion was observed off Pewet Island (fig.

7.37, 7.38), where anomalies arising from individual posts separated by c. 1m of soft sediment become notably broader with offset from the transceivers.

Because distortion in the transverse dimension becomes significant with offset, line spacing and orientation must be set to reduce the loss of information caused by poor textural contrast and smearing of targets into the general seabed backscatter. A line of individual posts at 50cm spacing will be resolved with range-dependent distortion if surveyed along an orthogonal survey track, but will appear as a single smeared lineation if passed on a parallel orientation. Work conducted at East Mersea Flats indicates that the increased survey costs incurred by working at multiple survey orientations can be justified in the quality of the resultant data. In rarely exposed sites such as those off Mersea Island, this may be the only method of constructing an accurate plan of the submerged structure.

Finally, a strong data set will only result from operating in calm sea conditions; the surface catamaran is vulnerable to surface swell which prevents the constant beam orientation necessary for operation at the optimum system resolution. Further modifications to the existing survey catamaran may serve to reduce system noise, but experience has shown that fine linear features quickly undergo insuppressible distortion if swell is encountered.

It is important to consider such marine geophysical equipment as representing elements of an inter-disciplinary family of tools suited to archaeological and site management purposes within the coastal environment. As suggested in chapter 6, each survey location is likely to require a different methodological approach, a statement borne out by the contrasting division of contribution made by the inter-disciplinary participants of the Strangford Lough and Blackwater Estuary surveys. The success of such surveys depends entirely upon the strength of interaction between the parties involved; in the case of the Blackwater, the provision of aerial survey coverage dedicated to examining side scan anomalies immediately after survey completion was an important step toward a total integration.

7.21: Conclusions

Intertidal deployment of side scan sonar as an archaeological reconnaissance and mapping tool has been tested at a number of locations and found generally suitable for this purpose, provided that the survey is properly planned. It is important that the nature of probable targets and seabed conditions is considered prior to commissioning a survey, if the optimum information yield is to be extracted. In summary, application of this technique within the intertidal zone has demonstrated that:

• Catamaran-mounted side scan sonar is a powerful tool for rapid, safe and accurate survey of the intertidal zone, providing high resolution, accurately positioned information upon the distribution of archaeological structures within otherwise inaccessible areas.

• The Saxon coastal fishing industry of Essex was of considerably greater extent than previously realised; the amount of material recorded in the SMR has been increased by approximately 5% to 250% at each site surveyed, as a direct result of marine geophysical survey.

• Significant subtidal structures exist off Pewet Island and probably also off Sales Point, which suggest that this method of fishing may have developed earlier than is presently accepted. Accurate mapping of this site should allow divers to collect samples to test this hypothesis by AMS ^{14}C dating.

• The Nass is the highest weir in the estuary and is therefore possibly the youngest. Future sampling directed at establishing the timing of decline in this method of fishing should be taken from this weir.

• Weirs in Strangford Lough and the Blackwater Estuary were constructed and developed to suit the prevailing conditions. A classification scheme based upon weir shape is thus of limited use as the variability in weir shape is likely to be as much a function of local controls as it is a measure of changing technologies or culture.

• The combination of aerial and terrestrial photography, field inspection and side scan sonar provides a robust intertidal survey methodology, which can be adapted to suit a range of shallow coastal environments. Future Management Plans for the coastal resource should make provision for this type of survey. Developers required to conduct intertidal surveys should also be required to adopt this level of survey, as a single method of investigation is unlikely to provide a full account of the local seabed resource.

Chapter 8: Discussion of Themes 1 & 2

Overview

This chapter is concerned with summarising the results of Themes 1 & 2 and discussing their implications for shallow marine, seamless inter-disciplinary surveys. This study has raised several methodological, archaeological and scientific questions, which merit further investigation; discussion of results therefore leads to suggestions for future work.

8.1: Introduction

Two separate Themes - seismic surveying of palaeolandscapes and archaeological seabed mapping using side scan sonar - have been pursued in this thesis. This division was made on the basis that palaeo-landscape imaging and archaeological mapping of the seabed involve different acquisition and processing techniques. In the following sections, the results of both Themes are briefly summarised; major points arising during this summary are flagged for more detailed discussion in section 8.4.

8.2: Summary of Theme 1

Theme 1 was concerned with the application of digital high-resolution sub-bottom profiling systems to the problem of mapping buried palaeo-landscapes in Strangford Lough, Northern Ireland. Such investigations require the routine post-processing of large seismic data sets; this can be extremely time-consuming and therefore expensive. Inspection and comparison of Boomer and Chirp data sets demonstrated that although these sources exhibit similar output signal frequencies, the repeatable and electronically calibrated nature of the Chirp pulse offers better resolution and greater potential for post-processing **(1)**. Combined theoretical and empirical analysis of the Chirp data allowed construction of a "generic optimum" processing flow, for rapid near-automatic processing of Chirp data, which has subsequently been successfully applied to data from other regions **(2)**.

Investigation of deposits dating from the late-Midlandian drumlinised tills (c. 19000 BP) to the present-day sediment distribution, indicated that local sedimentary environments have been greatly influenced by the drumlin landscape. A number of submerged, elongate features have been described as submerged drumlins, seismic images of which represent significant improvement upon those presented in the modern literature. These images suggest that drumlins arranged along an 8km line, orientated approximately parallel to the direction of ice flow, possess very similar internal structures. The general drumlin structure for this area is identified as comprising a stoss-end seismically transparent zone, fronting a set of shallow-angled (7-9°) leewards-dipping reflectors. This structure is overlain by a thin (1-2m) carapace of seismically unstratified till, and located above subtle topographic highs within the underlying glaciated surface **(3)**.

The late- to post-glacial relative sea level curve and sedimentary evolution of Strangford Lough were investigated by comparison of an extensive Chirp seismic data set with published work and core information obtained from sites on the northern shores. A high-resolution seismic stratigraphy was compiled and correlated with existing information **(4)**. Surface geometries within the lough agree with a general pattern of high late-glacial sea levels, falling to an early Holocene RSL minimum and recovering to (or exceeding) present levels, during the mid-Holocene. Identification of a minimum altitude of c. -20m OD for early Holocene erosion, suggests by comparison to published Irish Sea data, that Strangford Lough underwent a short period of isolation from the main marine body during this period. This may have important implications for early Mesolithic Irish settlement models **(4, 5)**.

8.3: Summary of Theme 2

Theme 2 investigated the application of side scan sonar to shallow marine reconnaissance and mapping of seabed structures related to the maritime cultural landscape. Surveying of extremely shallow sites was made possible by design and construction of a portable survey catamaran, capable of carrying both side scan transceivers and a Chirp sub-bottom profiling device **(6)**. Initial calibration of this system was achieved over stone fish traps in the inter-tidal zone of Strangford Lough, for which a large amount of control data was available. Tests demonstrated that the system is capable of detecting stone fish weirs in sandy and muddy seabed conditions and that it is possible to consistently map archaeological features across adjacent survey lines in extremely shallow (c.1.3m) water conditions. Field investigation facilitated calibration of individual anomalies with boulders eroded from nearby drumlins and demonstrated the potential for relying upon side scan sonar to provide a simple evaluation of whether a site is devoid of upstanding archaeological structures **(7)**.

Subsequent to calibration, a more detailed and extensive inter-disciplinary investigation was conducted in the Blackwater Estuary, an area where conventional survey techniques are limited by rising sea level, restricted tidal windows, expansive mud banks and poor visibility **(8)**. The targets in this instance were extensive Saxon wooden fish weirs, originally of inter-tidal position, but subsequently partially or entirely drowned by rising relative sea level. Side scan sonar was utilised to accurately locate extensive submerged structures, which had previously been only partially mapped and sampled. All sites surveyed were found to be of greater extent and complexity than previous investigations had suggested. The greatest success of this survey was the discovery and mapping of large submerged sections of wooden fishing structures within the subtidal zone off Pewet Island. This survey and ongoing work by local archaeologists working with Essex County Council, has demonstrated that fishing may have been a very significant element in the local economy, contrary to previous opinion **(9)**. Scientifically, an inability to image any significant element of the Collins Creek site raises the question of threshold conditions for reliance upon this technique, and emphasises the need for appreciation of these limitations by users of this equipment **(7)**.

8.4: Discussion

(1) Comparison of Chirp and Boomer signal properties by inspection of field data, rather than laboratory-acquired values, indicate that electronic calibration of the Chirp pulse and the use of a matched filter during routine correlation affords the more repeatable and therefore predictable signal. The major problem experienced with swept-frequency sources of the Chirp type is the limited transducer energy possible for safe, sub-cavitation oscillation, which limits the potential source penetration.

Results from Chapter 3 suggest that a higher-penetration Chirp profiler should provide a highly repeatable, broadband acoustic pulse, preserving resolution at greater depths. Such a system is currently under development as a joint venture between GeoAcoustics™ and the University of Southampton; improvements are focused upon the use of higher-power transducers, new sweeps weighted towards lower frequencies, and reduced internal electronic noise. A possible alternative to the use of Chirp sonar is the IKB Seistek™ line-in-cone array developed by IKB Technologies and UCNW Bangor (Richardson *et al* 1993, Simpkin & Davis 1993). This system attempts to improve signal-to-noise ratios by focusing the signal return onto the hydrophone, which is acoustically baffled against off-axis noise. Although the source does not offer the same degree of repeatability and user-defined frequency content, vertical resolutions comparable to Chirp are claimed for extremely shallow (2m) water depths. One practical disadvantage of this system is its bulk, which makes it far less manoeuvrable than the catamaran used in this study.

(2) The original reason for development of a "generic optimum" processing flow, was the need for acceleration in processing of the large Strangford Lough Chirp data set. This led to creation of a short processing flow capable of offering significant improvements in data quality, facilitated by the strong repeatability of the Chirp source. Application of this flow to 100km of Chirp data demonstrated the advantages of rapid processing in this manner. This processing flow has been used in several subsequent geophysical projects; situations where the user required substantial improvement in data quality, yet lacked the time necessary to thoroughly test every parameter. As the use of acoustic devices in maritime archaeology becomes increasingly widespread, there is an increasing requirement for archaeologists lacking geophysical training to become involved in the processing stage of marine surveys. Future investigations may thus rely increasingly upon the development of robust, reliable, processing tools such as the processing example described above, to improve inter-disciplinary overlap between maritime archaeologists and geophysicists.

(3) High-resolution marine seismology has been demonstrated to be a highly effective approach to the objective determination of drumlin internal structure and external form. The major advantage offered by this technique, is the ability to provide a rapid, continuous image of drumlin structure on any chosen orientation. This thesis has presented important new information on the internal structure of several adjacent submerged drumlins in Strangford Lough, which suggests that all of these morphologies formed in a similar manner. It has also provided evidence demonstrating that drumlins in this region form over subtle topographic highs on the underlying basal surface, contrary to several published hypotheses. Published accounts of drumlin investigation discussed in Chapter 5 indicate that even with core information, it is often impossible to determine the process of drumlinisation. Based upon the results of this chapter, it is justified to hypothesise that more intensive seismic study of Strangford Lough and similar areas may demonstrate widespread, subtle changes in internal structure, which relate to changes on a similar scale in subglacial conditions.

(4) Seismic data acquired in Strangford Lough supports the broad pattern of relative sea level change identified by Carter (1982) and Carter *et al* (1989), but offers additional information upon the magnitude of the early Holocene RSL minimum. A general seismic stratigraphy has been established for Strangford Lough, indicating widespread late-glacial deposition of draped surfaces, followed by RSL fall and erosion to a depth of c. -20m OD. Subsequently, rising RSL led to deposition of massively structured seismic facies, have been correlated with the Estuarine Clay described by several workers and summarised by Smith *et al* (1991).

The general seismo-stratigraphic architecture of Strangford Lough correlates strongly with published literature and core logs. The seismic data presented in this thesis possesses a vertical resolution of c.35cm (Appendix I), for coverage of 100km, representing substantial increase in the available amount of information on the evolution of the lough. The interpretation described in Chapter 5 suggests that the lough may have been isolated from the Irish Sea for a period of time during the early Holocene. Lack of sufficient accuracy in the RSL curve for the north-eastern coast (c.f. Carter, 1982) prevents accurate constraint of this period. A date of 13444 ± 120 yrs BP (Devoy 1983) for freshwater conditions at -1.3m OD in Roddans Port compared with the Carter curve suggests that RSL outside the lough fell c. 29m in a period of 4000 years. Assuming a linear rate of decay and recovery (likely to produce an underestimate) in RSL, it is hypothesised that the period of isolation was centred on c.9500 BP and lasted approximately 2700 years, during which the first settlers are known to have exploited local resources (McAuley, 1996). Future work involving a small number of cores would test this hypothesis; there now exists an accurate record of sediment thickness and distribution to guide palynological investigation of the lough.

(5) Why is an understanding of drumlin formation important to the maritime archaeologist? This is a question frequently asked by archaeologists, geophysicists and glacial sedimentologists, during assembly of this thesis.

Mapping of the upper bounding surface of submerged drumlins, reconstruction of the sedimentary evolution of the lough and refinement of the RSL curve allows steering of small-scale site specific investigations (i.e. excavation or underwater search) within very large regions. It has previously been acknowledged (e.g. Vernon 1971) that there is a link between early human settlement sites and the underlying drumlin topography, and location of such potentially preserved Mesolithic sites is archaeologically desirable.

The survey systems described and contrasted during this thesis provide the capability to image both sedimentological and anthropogenic material, as demonstrated in Strangford Lough. Division between geological and archaeological survey becomes less distinct at the resolutions afforded by these systems, particularly since interaction between physical processes and human activities is inevitable. It is suggested that a holistic approach to maritime archaeo-geophysical survey is not only more efficient (inter-disciplinary division of costs and labour), but will yield enhanced understanding of site distribution and preservation potential.

(6) The design and development of a novel combined survey platform has facilitated acquisition of data relating to both palaeo-landscapes and seabed artefact location, in water depths which were previously considered inaccessible to towed side scan sonar survey. Development of this catamaran represents a major step towards seamless intertidal archaeological survey. The catamaran is highly portable, stable and optimises the available side scan sonar slant range, producing extremely high quality data supplemented by accurate target positioning. Subsequent to survey work described in this thesis, this system was deployed in Lake Vättern, Sweden, where a post-survey target-truthing dive was placed directly onto a 2m square, 0.5m high target 500m offshore, demonstrating the positional repeatability afforded by this method.

Two possible technical improvements could be made to this system if environmental circumstances demanded. Firstly, the effects of turbulence should be addressed, to facilitate faster survey where necessary. The present design is towed directly behind the survey vessel, which can lead to reduction in data quality from prop wash turbulence. It should be possible to address this by forcing the catamaran further from the turbulence zone, by addition of a steering vane to the wash-side catamaran pontoon. The catamaran itself might also benefit from streamlining. Secondly, the present system of positioning the catamaran by reference to shipboard DGPS might be replaced by addition of a catamaran-mounted DGPS or RTK antenna. Both of these changes are relatively minor, however, as the present system has been demonstrated to be highly effective in its current state.

(7) How much reliance can be placed upon intertidal side scan survey by the method described in this thesis? It is important to appreciate the likely limits of any survey tool, if misinterpretation is to be avoided, particularly if the data suggests an absence of seabed material. Data from Pewet Island demonstrates that this method can clearly resolve individual uprights within fishing structures, given a low angle of incidence and high acoustic contrast with the seabed. Correlation with field reports (Bruce, 1993) also demonstrates that scattered material such as hurdling, bricks and shell trapped around structures can be imaged. Two sites within the estuary demonstrate possible limitations of the survey technique:

Firstly, side scan images of the East Mersea Flats were of mixed quality; despite imaging a significant amount of newly identified structure, known sections of the weir were not detected. This site is very exposed; during the two-day survey period, the area experienced intermittent swell of 30-40cm, which is sufficient to significantly degrade high-frequency side scan signal return. This reduction in signal quality was compensated for by acquisition of data in three contrasting orientations, which considerably improved the information yield.

Secondly, the acoustic contrast between likely targets and seabed cover requires consideration, as demonstrated at a single locality by data from the Nass. Where wooden structure crosses from a soft sediment area of low textural roughness (south bank of the Nass) to a region containing bedforms comprising coarser sediment (north side), the resultant rise in background backscatter levels makes differentiation between archaeological and sedimentological targets difficult.

These problems can be addressed in the manner employed during the Blackwater survey. Increasing the number of survey grid orientations is good practice, regardless of sea conditions, as targets are rarely uniform in dimension, and multiple perspectives aids 3D visualisation during interpretation. The likely effects of sediment roughness and seabed topography can be estimated by pre-survey inspection of aerial photographs and / or grab samples. In summary, if the physical context of sonar acquisition is understood and conditions are known to be favourable, then this method should be considered very reliable for determination of the presence or absence of intertidal seabed structures such as coastal fish weirs.

(8) Conditions in the Blackwater Estuary are unfavourable to site reconnaissance by terrestrial means; the infrequently exposed, soft sediment environment is hazardous and unpredictable. Aerial survey of the region represents a more effective approach, but sufficient exposure is rare, necessitating winter flights in low light conditions. Neither of these methods is capable of providing rapid, accurate plans of the wooden fishing structures known to lie on the more seaward mudflats of the region, nor can they investigate structures drowned by rising RSL and permanently submerged within the subtidal zone. A marine approach involving high frequency catamaran-mounted side scan sonar has been demonstrated to represent an effective tool for seamless survey of the subtidal and intertidal environments. It is important to acknowledge that this methodology will only be properly effective where a fully inter-disciplinary approach is supported by provision of information through aerial photography and local archaeologists.

Results from the Blackwater Estuary demonstrate that the true extent of coastal exploitation sites is often greater than immediately suggested by observations recorded in the SMR (c.f Quinn *et al*, 1998a). Side scan sonar survey of wooden structures at Pewet Island and Sales Point has discovered substantial structure within the subtidal zone, whilst it is also suggested that structures on East Mersea, West Mersea, The Nass and Collins Creeks are more extensive than previously perceived. In addition to improving understanding of how these structures operated (see following point), this is crucial to delimitation of monument size, for entry to the National Monuments Record, and any resultant site protection.

In conclusion, it is proposed that future studies and Management Plans for areas containing extensive intertidal regions and a history of transgressive RSL should consider adoption of a survey methodology based upon the successful approach developed in the Blackwater Estuary.

(9) Primary historical information upon Dark Age (early to middle Saxon) England is rare. Information resulting from the combined inter-disciplinary survey of inaccessible areas described in this thesis has demonstrated that fishing structures were of far greater extent than previously expected. The presence of a previously unidentified major fishing component within the industries of the Saxon period will have important implications for the archaeology and history of Essex.

Images from East Mersea Flats and Sales Point have revealed possible locations for access walkways, which when further investigated may improve our understanding of the manner in which these weirs were operated. Using positions supplied from side scan sonar interpretations (figs. 7.27, 7.31) it should be possible to study the remains of these walkways and to determine whether they were likely to be capable of supporting horse-drawn carts for servicing the weirs and exporting the catch. This may provide an indication on the significance of these fisheries within the cultural landscape, i.e. was fishing by this method largely a subsistence activity involving a small number of individuals (no need for bulk transport of fish) or was a large catch regularly exported inland for sale to the local populace?

It is also hypothesised that these weirs would be associated with other elements in the landscape, particularly small boats and associated landing places. Where large amounts of timber were to be ferried across the flats to remote fisheries, the easiest method may have been to prepare the stakes and hurdles onshore, and then float them out to the site on high tide. It is possible that areas for preparation of stakes, construction of hurdling and assembly of materials for transport existed in what is now the upper region of the inter-tidal zone. A more intensive field study should be considered, using the newly obtained accurate fishery locations to predict and examine potential areas of associated activity.

Side scan sonar investigation of coastal fish weirs at Pewet Island and Sales Point has revealed that these sites extend significantly into the subtidal zone, and has also revealed the presence of additional, previously unseen structures. On the basis of rising relative sea level, it has been hypothesised (Chapter 7) that the most seaward structures at these sites may be older than their contemporaries on the northern shores, and demand further investigation. Current thinking suggests that coastal fishing practices in Essex may have developed in response to increased pressure on the hinterland, during the collapse of the Romano-British infrastructure. This proposal might be tested by sampling of wood extracted from the most seaward of the newly discovered structures at Pewet Island.

This thesis has presented data emergent from a nascent research discipline - the study of an area whose archaeological record will only be understood if viewed from the overarching perspective allowed by acceptance of the Maritime Cultural Landscape. The discovery of a major fishing component within the industrial and social structure of Saxon Essex sits uneasily against established, published perception of Saxon life (e.g. Murphy, 1994). If true understanding of this period is to be achieved, it is imperative that historians and archaeologists reconsider existing evidence from the perspective of marine-terrestrial interaction across the intertidal zone. In particular, the presence of the fishing industry will alter our understanding of animal husbandry, agriculture, trade, woodland management and the importance of access to coastal areas. The interdisciplinary survey methodology presented here has proved capable of providing spatial and quantitative information of the scale and location of the Saxon fishing industry - in effect a base level of factual data for construction of future models. A fresh approach to this area, based upon the precept that interaction between maritime and terrestrial economy is an inevitable, controlling factor in landscape evolution, may produce radically different economical models for coastal economies during the Dark Ages.

Chapter 9: Conclusions

This thesis has discussed the use of high-resolution digital seismic survey techniques as a tool for landscape investigation. Emphasis has been placed upon the benefits arising from an inter-disciplinary approach to maritime archaeological problems within the shallow coastal environment. Thesis content has concentrated upon three main areas of research: investigation of palaeolandscapes and coastal evolution, rapid inter-disciplinary mapping of intertidal and subtidal archaeological structures, and the associated practicalities of shallow water acquisition, processing and interpretation of digital seismic data.

Conclusions and hypotheses relating to individual studies within this report were presented in previous chapters. Overall findings arising during this investigation are as follows:

- High-resolution seismology provides a means of rapid, non-destructive, accurate mapping of both buried palaeolandscapes and submerged elements of the cultural maritime landscape. These targets may be located in regions otherwise virtually inaccessible to archaeological investigation, such as the inter- and subtidal mud flats of the Blackwater Estuary, Essex.

- Combination of Boomer and Chirp sub-bottom profilers is an effective means of studying physical landscape evolution, for investigating the structure of drowned subglacial bedforms and for studying the sedimentary evolution of landscapes in response to fluctuating relative sea level. Study of palaeolandscapes is essential to understanding the context of archaeological sites in a changing coastal environment.

- Drumlins in Strangford Lough, Northern Ireland, exhibit a common internal structure and relationship with underlying topographic maxima on the underlying basal surface. This is the first time that it has been possible to study multiple, adjacent drumlins in an accurate, objective and non-destructive manner.

- Seismic evidence supports the hypothesis that Strangford Lough underwent isolation from the Irish Sea during the early Holocene (c. 9500 BP). Early Mesolithic exploitation of Strangford Lough may therefore have been driven by attraction to a freshwater resource, rather than a sheltered marine environment.

- Deployment of 500 kHz side scan sonar on a specifically designed survey catamaran has facilitated mapping of submerged wooden structures, with a nominal accuracy of ±1m. Accurate mapping of such structures facilitates improved understanding of the scale and manner in which these sites operated, and their importance within the cultural maritime landscape. It is argued that future site investigation and management plans should adopt a multi-disciplinary approach based upon aerial reconnaissance, high-resolution seismology and subsequent field inspection.

- The Saxon coastal fishing industry of Essex was of substantially greater extent than previously recorded. Combination of side scan sonar, aerial photography, historical research and field inspection has provided accurate plans of wooden structures located within inaccessible areas of the inter- and subtidal zones in the Blackwater Estuary. It is suggested that newly located subtidal structures at Pewet Island and Sales Point may represent remnants of an earlier phase of the coastal fishing industry. Dating of these discoveries may assist in determination of the timing and motivation of development of this fishing technique in Essex.

- A final, critical conclusion must be drawn from both data presented in this thesis and the author's experience in acquisition, background research, presentation and publication of the information presented herein. It has been demonstrated that the innovative use of high-resolution marine seismology can facilitate reliable, quantitative study of areas traditionally considered inaccessible. The generic adoption and development of a Maritime Cultural Landscape concept is a striking example of how traditional single-disciplinary studies have failed to understand and acknowledge the importance and inter-dependency of process, landform and anthropogenic activity in evolving landscapes. This problem is widespread, extending to the links between archaeology and physical processes and beyond. A holistic approach to future research into glacial, marine and terrestrial processes will be vital, if landscape evolution is to be properly understood. Implicit in this approach is that workers in established research disciplines adopt a global perspective and to this end, accept and encourage the use of new techniques from neighbouring fields to investigate long-standing problems, the rewards for which have been demonstrated in this thesis.

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Appendix I: Post-Processing of Digital Marine Chirp Data

AI.1: Introduction

The digital acquisition of Chirp data facilitates signal enhancement by post-survey laboratory-based processing on a dedicated software package[1]. The processing of high-resolution marine seismic data acquired with a swept frequency (Chirp) source comprises two major stages (Quinn 1997, Quinn *et al* 1998b). Firstly, the correlation sweep (Chapter 2) may be optimised, such that a sharp spike results from each reflection event; this is known as *pre-processing*. Subsequently, the clarity of the resultant correlated seismic section may be enhanced, following analysis of the acoustic frequency content of the data. The signal-to-noise ratio (SNR) and lateral coherency of the signal within sections are then improved by the application of selected signal-enhancing algorithms. This second stage is termed *post-processing*.

Data gathered for the studies described in this thesis were acquired in both uncorrelated and correlated states. Real-time correlation was conducted during acquisition, using a correlative sweep pre-programmed by the system manufacturer[2]. For surveying submerged archaeological sites, a rapid, robust and widely applicable method of producing high-resolution sections is necessary. The final processing flow should enable rapid evaluation of large data sets whilst requiring minimal alteration of the algorithm parameters within individual seismic lines or even between different geographical areas. Such a brief would be impossible to contemplate, if it were not for the highly repeatable nature of the Chirp source, in which the uncertainties associated with source variability are largely removed, reducing the major unknowns to the earth response and ambient / electronic noise (Schock & LeBlanc, 1990).

Subsequent to the work of Quinn (1997) it was decided to commence processing at the post-correlation stage, using the default correlation sweep employed by the GeoAcoustics™ Sonar Enhancement System V3.4.

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[1] A number of oil-industry software packages are available; the package used in the SOES is Advance Geophysical's ProMAX™ 6.0 and more recently 98.1, which is operated on a network of Sun and Solaris workstations. All data exhibited in this thesis was processed in version 6.0 unless otherwise stated.

[2] GeoAcoustics Ltd, Great Yarmouth, UK.

AI.2: Optimal Post-Processing of Correlated Chirp Data

Post-processing is effected by passing seismic data through a number of sequential algorithms, which are selected and adjusted in sympathy with the data properties. A wide range of algorithms have been developed for use with the acquisition arrays more commonly used within the oil industry; some of these algorithms are suitable for application to correlated Chirp data, and are available within ProMAX™.

Prior to processing Chirp data from Strangford Lough and the Blackwater Estuary, the suitability of numerous algorithms was evaluated on the grounds of both the resultant improvement in data quality and the ease of transferral between applications, (i.e. whether a particular algorithm requires vastly different control parameters for differing sub-bottom structures or reflectivity profiles). The resultant flow is described in fig. A1.

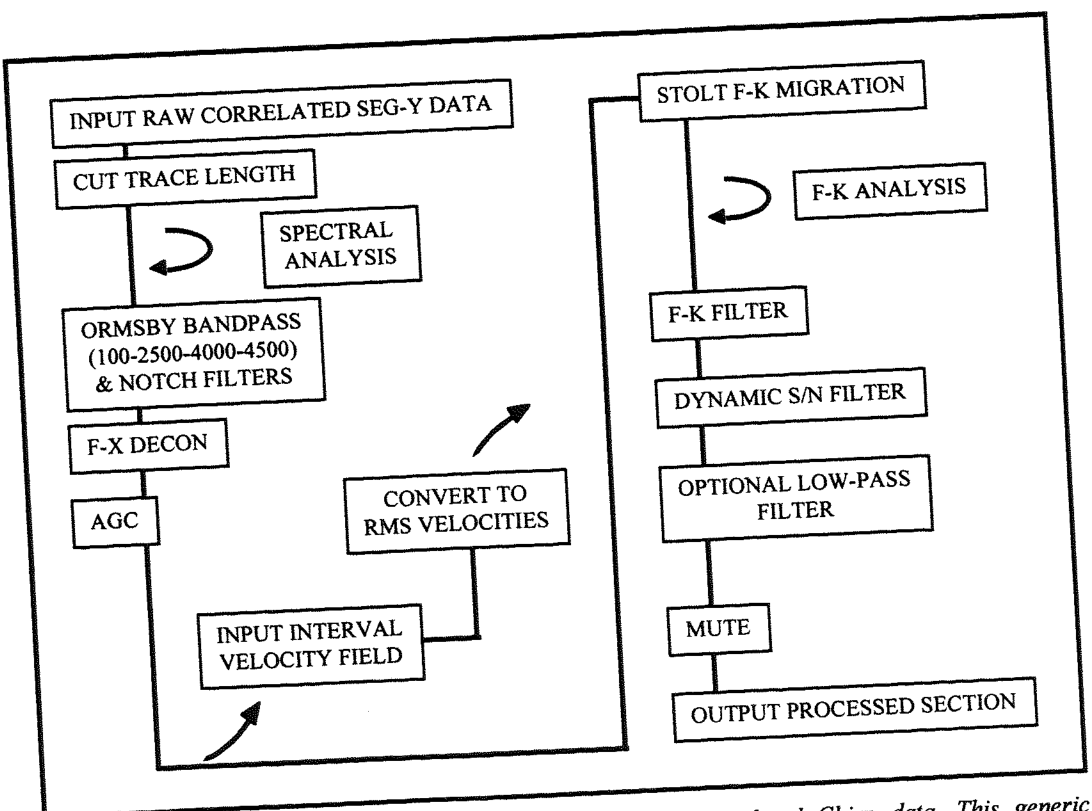


Fig. A1: Optimum processing flow for post-processing of correlated Chirp data. This generic processing flow has been applied to data from Strangford Lough, the Blackwater Estuary, Mary Rose wreck site and Lake Vattern, Sweden, requiring only minor modifications to the input parameters.

Acquisition of Chirp data over the Blackwater and Strangford Lough sites was effected with a GeoAcoustics GeoChirp profiler (transducer model 137D) utilising a 2-8 kHz 32 ms sweep sampled at 40 μs and transmitting at 4 pulses per second. Data displayed within the main body of this thesis is correlated data in either its raw state, or at the final, fully-processed level. It is intended that the following figures should expand on this to graphically describe the individual stages of the processing flow, although without the full mathematical justification for each flow element, for which the reader is referred to a standard text, e.g. Sherriff & Geldart (1982) or Yilmaz (1987).

Input Raw Correlated Seg-Y Data
Cut Trace Length
Spectral Analysis

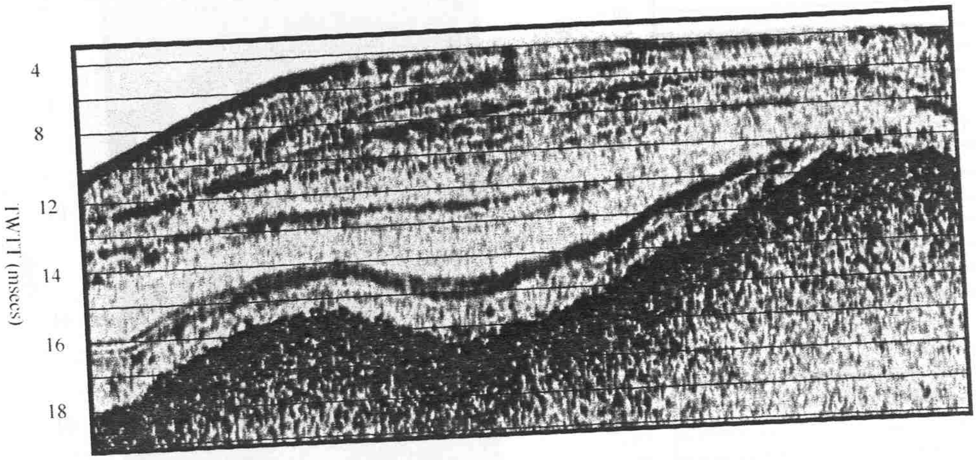
A section[3] of raw correlated Chirp data is displayed in fig. A2a, and the overall frequency content of 151 traces within this section (CDP 3050-3200) is shown below this (fig A2b). Trace lengths are reduced from the standard record length of 133 ms to 50 or 60 ms in order to improve the speed of processing for data gathered in shallow environments. The frequency content of the recorded correlated pulse exhibits a maximum at approximately 200 Hz, which dominates the power spectrum and masks the contributions of seismic energy present up to 4500 Hz. The final stage of the correlation sequence is the calculation of *instantaneous amplitude* R(t) whereby:

$$R(t) = (x^2(t) + y^2(t))^{0.5} \qquad \text{(Eqn. A1).}$$

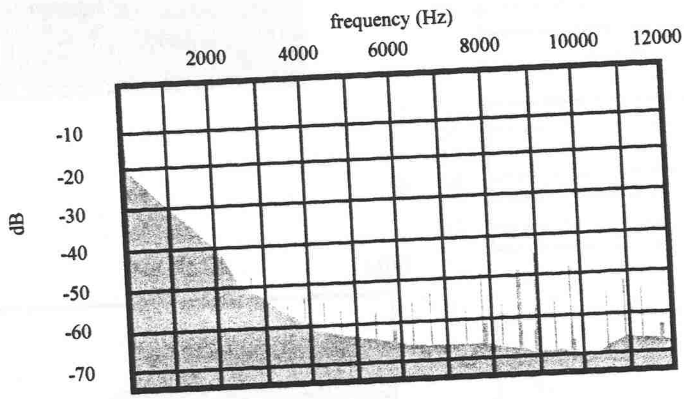
In this expression, the instantaneous amplitude is calculated as a function of the signal x(t) and quadrature y(t) (Taner *et al* 1979, Yilmaz 1987), in order to replace the high-frequency wavelet resultant from correlation with a single spike whose energy

[3] All processing sections exhibited are taken from Strangford Lough line 3013, a line orientated ENE-WSW on the western flank of Strangford Lough's central basin. This line was selected for flow testing because it contains a large number of interesting sedimentary contacts and relatively steep reflector gradients.

represents the total reflection strength. The frequency content of the resultant broad positive spike is thus down-shifted to a bandwidth of 0-4.5 kHz.



(a)



(b)

Fig. A2: (a) Raw correlated Chirp section from Strangford Lough. Note the lateral variability in reflector coherency along the section, which is due to noise. (b) Power spectrum of the displayed section, indicating that the modal frequency lies at c. 100-200 Hz, although there is signal present up to 4500 Hz. Spikes present from c. 2750 Hz are manifestations of electronic noise within the acquisition system.

The Chirp source signature employed is weighted in order to limit the downwards reduction in bandwidth as a result of attenuation with depth. This weighting is applied to counter the effects of acoustic attenuation in sediments, an effect proportional to signal frequency (fig. A3). Preservation of bandwidth at depth reduces the loss of vertical resolution at increased penetrations, whilst allowing the processor to employ a simple time-invariant bandpass filter to the data.

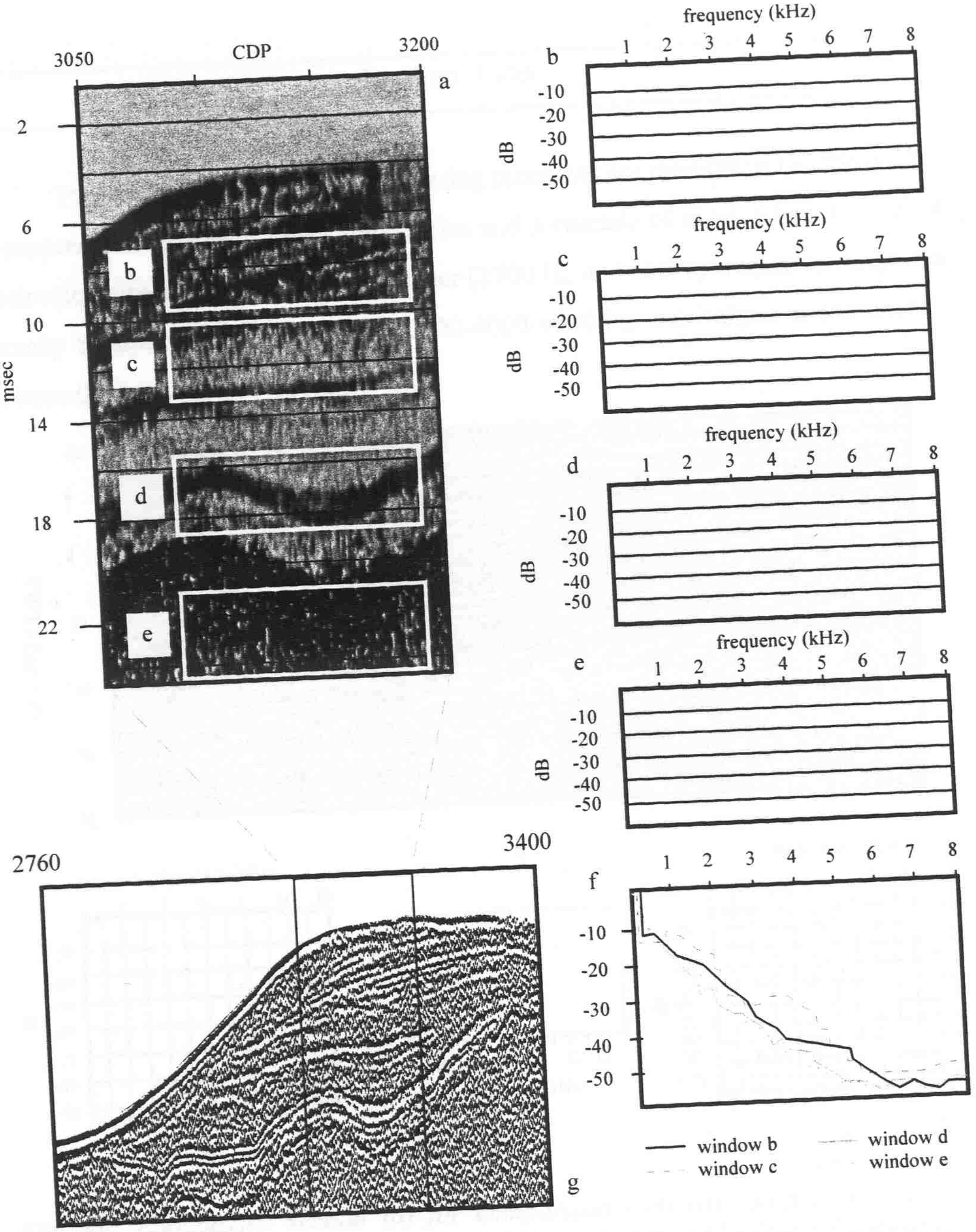


Fig. A3: Analysis of time-variant frequency content in a Chirp pulse attenuated by passage through soft sediments, Strangford Lough. Four discrete t-x windows (b,c,d,e) within the raw data (a) are spectrally analysed and their corresponding power spectra extracted and superimposed (f) (N.B. Noise created by electronic interference has been removed for display purposes). There is little change in the spectral power distribution with depth; this is a consequence of Gaussian shaping of the Chirp source signature. The location of this test is placed in context in window (g).

Bandpass Filter

Two initial frequency domain filtering processes are required: a bandpass filter to suppress the dominant lower frequencies and a cascade of notch filters to remove electronic noise spikes present in the upper (2700 Hz and above) frequency range. An Ormsby bandpass constrained at 100-2500-4000-4500 Hz was judged to consistently produce the best results (fig. A4).

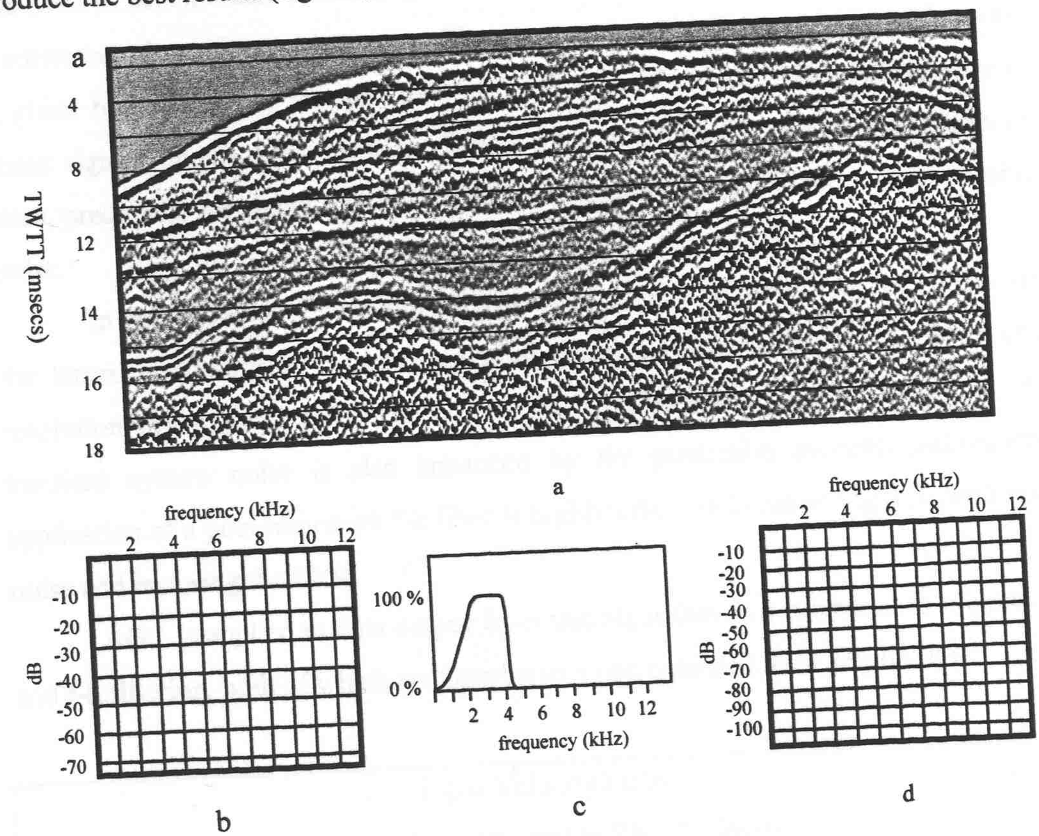


Fig. A4: Bandpassed section (a) for comparison with raw data in fig. A1. The frequency spectrum of unprocessed data (b) was dominated by lower frequencies (c. 100-200 Hz) and afflicted by high-frequency electronic system noise. Application of an Ormsby bandpass filter (c) and cascaded notch filters (not shown) has the effect of up-shifting the dominant frequency to c. 1200-1500 Hz (d), by heavily attenuating the previously dominant low frequency contributions.

The argument for using a minimum phase filter rather than zero-phase was based upon the almost negligible improvement in data clarity afforded by the minimum phase filter. There is some debate between theoretical seismologists as to whether the concept of minimum phase signals can be applied to real seismic data

(Goulty, *pers. comm.* 1998), and thus it should be explained that this filter mode was selected empirically.

FX Deconvolution Automatic Gain Correction

FX deconvolution is a frequency-domain prediction filter designed to boost the SNR of seismic data containing consistently dipping reflection events. Following Fourier transformation, such events will appear as sinusoidally complex signals across a given frequency slice (ProMAX™ 6.0 User Manual, 1995). The predictability of these signals allows a complex prediction filter to be passed across the frequency slice, predicting the signal one trace ahead and treating any differences as removable noise.

In practice, F-X deconvolution was found to be a powerful tool for enhancing the lateral continuity of reflections within Chirp sections, although the SNR and resolution are initially significantly reduced by application of this algorithm, as transient system noise is also enhanced by the prediction process. Subsequent application of a post-migration f-k filter is highly effective in removing this persistent noise and restoring the SNR.

AGC is applied to data output from this algorithm as a precursor to migration and f-k filtering, both of which perform better upon balanced trace amplitudes.

Input Velocity Field Convert from Interval to RMS Velocity

For migration to be successful, an estimate of the velocity field through the section is required. Despite attempts to gather velocity information using land refraction techniques on the exposed inter-tidal zone in Strangford Lough, it has not been possible to accurately reconstruct the velocity field of the sediments surveyed in Strangford Lough or the Blackwater Estuary. Future developments in high frequency marine refraction seismology may alleviate this highly significant problem, by providing integrated reflection-refraction data. In the absence of accurate velocity constraints, estimates of the velocity field are made with reference to published velocity tables, e.g. Hamilton 1971, Jensen *et al* 1994. The fields constructed are extremely simple; a typical velocity section will contain three fields representing the water column, recent deposits and underlying acoustic basement. The introduction of vertical and lateral velocity gradients to account for compaction has not been successful, producing visible distortion during migration (see below).

Stolt F-K Migration

The Stolt f-k migration algorithm (Stolt, 1978) offers two major advantages over other migration types, making it the most suitable for inclusion in a generic processing flow. This algorithm is both the fastest migration process available, and also one of the most simple to implement. The input velocity field for Stolt f-k data migration should be as simple as possible, making it well suited to the situation where all input velocity values are estimates. The algorithm converts the data by proportionally "stretching" all velocity regions relative to the lowest contained in the input model - producing a pseudo constant velocity section - before migrating the entire section at this constant minimum velocity. The effect of migrating a short section of Chirp data is displayed in fig. A5.

F-K Analysis
F-K filter

F-k (frequency-wavenumber) filters are employed to remove noise events whose frequency content coincides with the desired signal. These events tend to become more pronounced as a result of f-x deconvolution, but are easily removed after an initial iterative application of the f-k analysis and filter testing (fig. A5). The major disadvantage of applying the f-k filter lies in its potential for removing steeply dipping sections of seismic reflectors; its use requires careful design and sometimes selective application.

Dynamic S/N Filter

This filter enhances the lateral coherency of data by weighting each frequency by a function derived from the local signal-to-noise ratio (ProMAX™ 6.0 User Manual, 1995). It differs from other similar processes such as the f-x decon algorithm because although the filter applied to each trace is derived from the properties of the surrounding traces, there is no element of trace mixing involved in the actual filter convolution. Consequently there is no lateral smearing involved in this process. The weighting is applied to each frequency in proportion to the SNR, such that frequencies containing a low signal content are suppressed relative to those with higher ratios.

Substitution of this process in place of the early f-x deconvolution processing stage results in a visibly cleaner image in which the lack of smearing is evident. However, the resultant data does not migrate well, and the final sections contain a greater level of noise than if the f-x deconvolution had been employed. Use of this algorithm post-migration offers only a small improvement in section clarity (fig. A5).

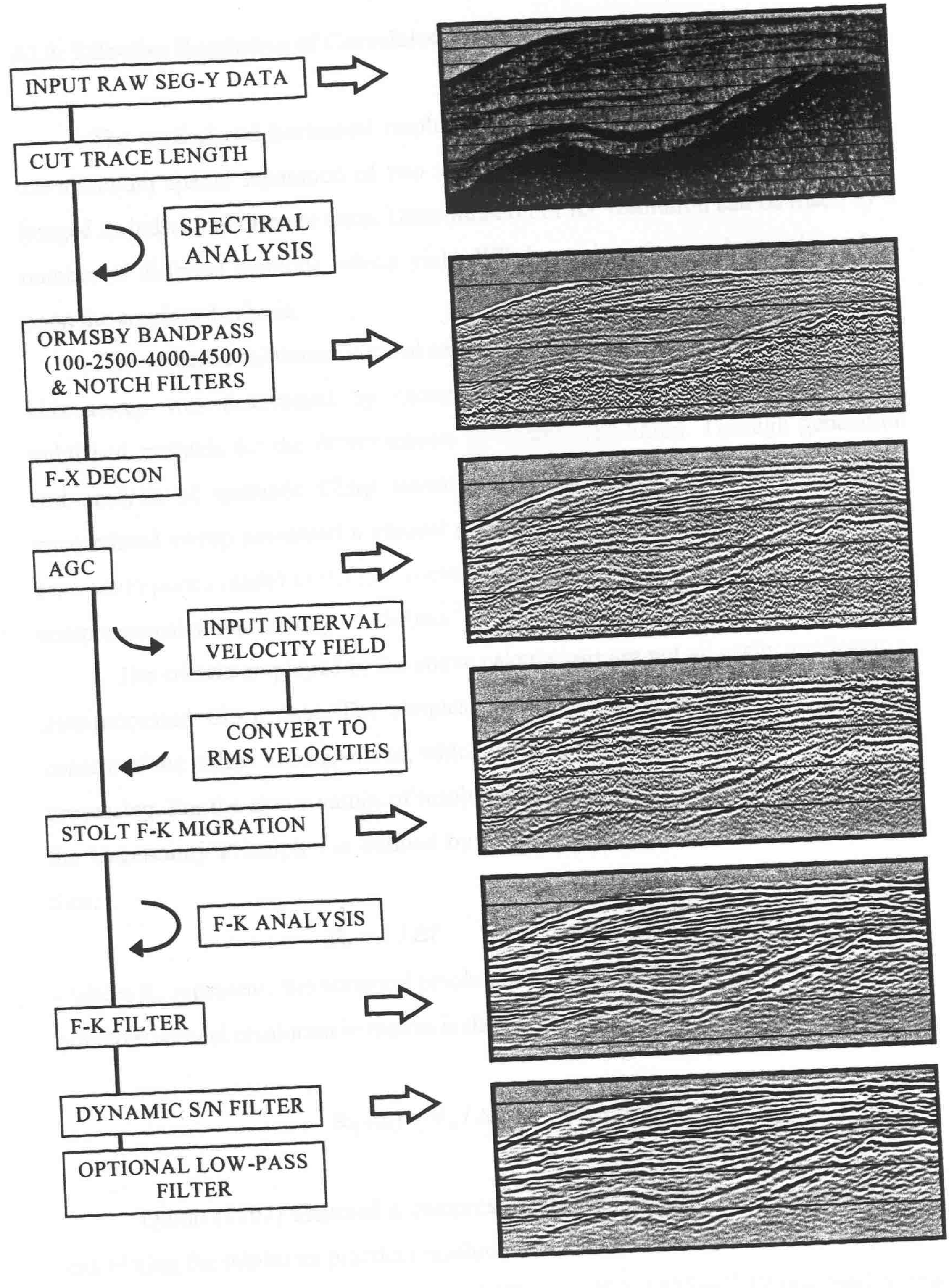


Fig. A5: Processing flow elements with accompanying stage-by-stage representation of data improvement in a short section of seismic data from Strangford Lough. Section dimensions are approximately 175 x 19 m. All post-processed data exhibited within this thesis was processed with the flow described in this figure.

AI.3: Effective Resolution of Correlated Chirp Data

The vertical and horizontal resolution of seismic data are loosely defined as the minimum spatial separation of two reflecting bodies such that they can still be imaged as individual discrete units. Determination of the resolution can be made by a number of different methods, which yield differing values for resolution dependent upon the employed criteria.

The effective minimum vertical resolution of the uncorrelated GeoChirp™ 2-8 kHz sweep was determined by Quinn (1997), who examined seven differing published methods for the determination of vertical resolution. Through generation and analysis of synthetic Chirp seismograms Quinn (1997) determined that the uncorrelated sweep possessed a vertical resolution which ranged from 0.25m (worst case assumptions made) to 0.125m (best-case conditions), in sediments possessing a compressional-wave velocity of $1500 ms^{-1}$.

The criteria employed in the above calculations are not all easily applicable to post-processed Chirp data. The simplest are those which consider the frequency content of the pulses to be resolved, which is easily determined during and after post-processing. For the above values of resolution, Quinn (1997) employed the criteria of the Uncertainty Principle (as defined by Clarebout 1976 and Clay 1977), rewritten thus:

$$R_v = 1 / \Delta f \qquad \text{(eqn. A2)}$$

- where R_v represents the temporal resolution of a source of bandwidth Δf Hertz. The effective vertical resolution in metres is then given by:

$$R_v\,(m) = V_p / \Delta f \qquad \text{(eqn. A3).}$$

Quinn (1997) assumed a compressional wave velocity (V_p) of $1500\ ms^{-1}$, in calculating the minimum practical resolution for uncorrelated data. In this study, three values of velocity are utilised: $1500 ms^{-1}$ (Quinn - V_q), $1575 ms^{-1}$ (Value used during migration - V_{mig}) and $1685 ms^{-1}$ (Mean sediment compressional wave velocity calculated from Hamilton, 1971 - V_h). The signal bandwidth after bandpassing is

4500 Hz, yielding minimum practical vertical resolution values of $V_q = 0.33m$, $V_{mig} = 0.35m$ and $V_h = 0.37m$.

The most commonly used criterion is that of Yilmaz (1987) who defines vertical resolution thus:

$$R_v\,(m) = V_p / 4\,f_d \qquad \text{(eqn. A4)}$$

where R_v (m) is the resolution in metres, V_p represents the seismic p-wave velocity of the sediments (ms^{-1}) and f_d is the dominant frequency of the seismic pulse, in Hertz. From spectral analysis of correlated data (e.g. fig. A4) the dominant frequency of the bandpassed Chirp pulse lies between 1000 and 1500 Hz. This yields values of V_q= 0.25-0.375m (mean 0.31m), V_{mig}= 0.26-0.39m (0.33m) and V_h= 0.28-0.42m (0.35m).

The above calculations indicate that similar values for resolution arise when either bandwidth or dominant frequency is the determinant criterion. As the downgoing Chirp pulse maintains its Gaussian frequency spectrum and bandwidth with depth (fig. A3), the correlated signal therefore has a vertical resolution of approximately 0.35m, increasing with depth as a result of cumulative effects of scattering and pulse attenuation.

The horizontal (lateral) resolution of a seismic source is conventionally determined by the width of the first Fresnel zone, a circular area on a reflector whose size depends upon the depth to the reflector, the velocity above the reflector, and the dominant frequency (Yilmaz, 1987). The Fresnel zone is considered to represent the minimum lateral spacing of two reflecting points such that they may be individually resolved in seismic section. Lateral resolution is calculated thus:

$$r = (z\lambda / 2)^{0.5} = (v/2)(t/f)^{0.5} \qquad \text{(eqn. A5)}$$

where r represents resolution (m), z the depth to the reflector (m), v the compressional wave velocity (ms^{-1}), t the two way travel time (s) and f the dominant frequency of the incident pulse (Hz).

Dominant Freq. (Hz)	Velocity (ms^{-1})	TWTT (s)	Resolution (m)
1250	1575	10	2.2
1250	1575	20	3.15
1250	1575	30	3.86
1250	1575	40	4.45
1250	1685	10	2.35
1250	1685	20	3.37
1250	1685	30	4.13
1250	1685	40	4.77

*Table A1: Lateral resolution in terms of first Fresnel zone width (metres) for a correlated Chirp pulse attaining penetrations up to 40 ms in sediments of typical velocity 1575*ms^{-1} *and 1685*ms^{-1}.

As described in Chapter 2, the use of four transducers in the Chirp source generates a constrained acoustic footprint which is a function of the source (uncorrelated sweep) frequency content. The acoustic beamwidth varies with frequency thus:

Frequency (kHz)	Beamwidth (°)
3.5	55
5.0	45
7.0	35

Table A2: Frequency - beamwidth values for the GeoAcoustics GeoChirp transducer array, as presented by Quinn (1997) and courtesy of GeoAcoustics Ltd.

Assuming a RMS compressional wave velocity of 1575ms^{-1}, the median frequency (5 kHz) has a footprint 6.5m in diameter at 10 ms TWTT, and 19.6m at 30 ms TWTT. The acoustic footprint diameter is always greater than the width of the first Fresnel zone, although at very short travel times (less than 10 ms TWTT) values for the two are convergent. The Fresnel zone lies within the acoustic footprint area, as is the standard case for a non-focused source such as an airgun array with a spherically spreading pulse. The concept of the Fresnel zone thus appears equally applicable to the Chirp source, therefore the Fresnel zone diameter, rather than the acoustic footprint width, describes the lateral resolution of the Chirp pulse.

Appendix II: Fold-out copy of seismic line 502, supplementary to Chapter 4.

This seismic section represents original ship-board printout of Boomer profile 502, described in Chapter 4. A reduced, annotated version of this plot is presented in fig. 4.11. Data in this section has been band-pass filtered at 200-2000 Hz. Horizontal timing lines are spaced at 10ms, whilst vertical markers represent approximately 600m of offset along the survey track.

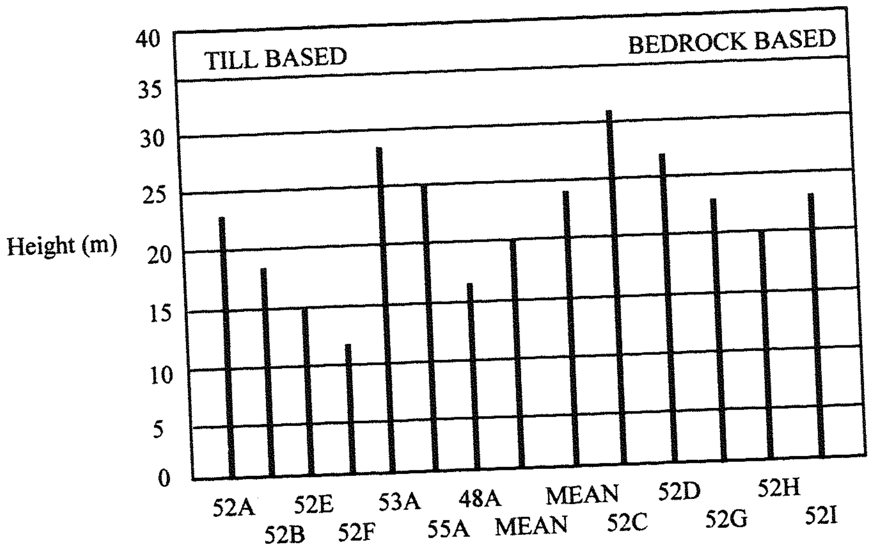
Appendix II: Fold-out copy of seismic line 502, supplementary to Chapter 4.

This seismic section represents original ship-board printout of Boomer profile 502, described in Chapter 4. A reduced, annotated version of this plot is presented in fig. 4.11. Data in this section has been band-pass filtered at 200-2000 Hz. Horizontal timing lines are spaced at 10ms, whilst vertical markers represent approximately 600m of offset along the survey track.

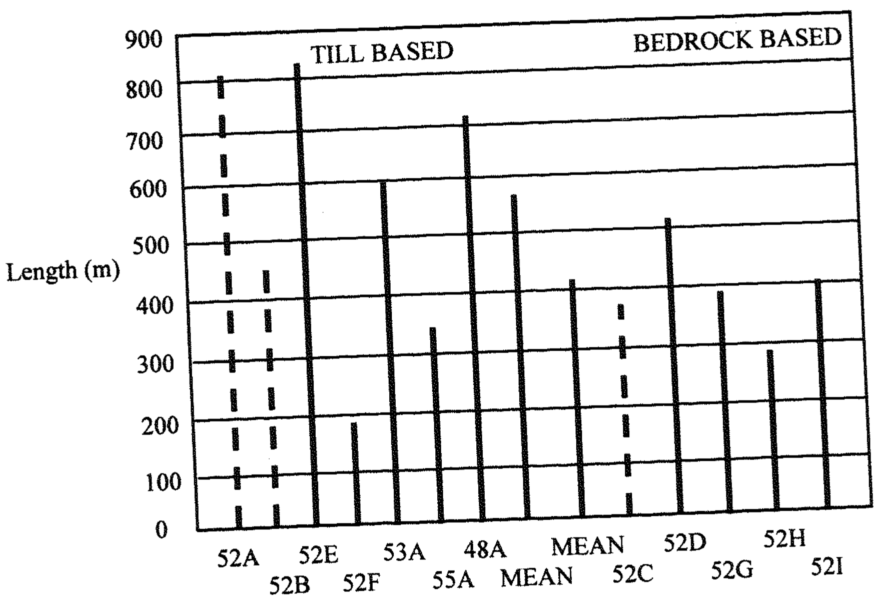

turned 336 degrees

Appendix III: Measurements of Drumlins Extracted From Strangford Lough Seismic Data

This appendix contains measurements from 13 drumlins surveyed in central and northern Strangford Lough (fig. 4.10). These results form the basis of discussion in Chapter 4.



Drumlin maximum height



Drumlin lengths (m). Dashed lines indicate north-south survey transects, solid lines correspond to NNW-SSE