Declaration

This thesis has been composed solely by myself. The work presented is my own unless otherwise acknowledged.
The Sedimentary Evolution of the lower
Paleogene of the East Shetland Basin

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ABSTRACT

Application of a pragmatic seismic and sequence stratigraphic methodology to the lower Paleogene of the Northern North Sea shows that seven depositional episodes can be identified in areas of good data coverage. The Maureen, Andrew, Lower Balmoral, Upper Balmoral, Forties, Sele and Balder sequences are broadly equivalent to those observed in the Central North Sea (Mudge & Copestake, 1992a). Correlation of these sequences through a regional database (2600kms of regional 2D seismic, 158 wells, biostratigraphy from 31 wells, and limited core data), and in two key study areas on the basin margin (the Bressay discovery covered by a 500m 2D seismic grid) and in the basin centre (the Ninian oil field covered by two 3D seismic surveys), allows the construction of a detailed stratigraphic model for the Early Paleogene of the Northern North Sea.

The data indicate that the earliest sedimentation in the basin (Maureen sequence) was limited, and sporadically distributed. This was succeeded by very significant rejuvenation of the hinterland, recorded by arenaceous deposition (the Andrew / Lower Balmoral sequences) in two distinct sub-basins: the Viking Graben and the East Shetland Basin. Of these, the Viking Graben depocentre predates the East Shetland Basin depocentre. The timing of the switch between the sub-basins is possibly concomitant with transgression of the East Shetland Platform in the North Viking Graben. Deposition in the depocentres was coeval with the lateral accumulation of thick shale successions. Regression of the basin margin occurred again during the Upper Balmoral sequence, but sediment accumulation in the basin was principally argillaceous. The subsequent Forties sequence regression is marked by incision of fluvial systems on the East Shetland Platform, and supply of sediment to the Viking Graben via canyons in the Bressay area. Base-level fall is again observed in the basin during the Sele sequence, which led to re-incision and re-occupation of the incised-valley systems at the edge of the platform. The magnitude of the Sele sequence incision in the Bressay area is not as great as observed in the Forties sequence, and progradation did not reach the edge of the East Shetland Platform. In contrast, high rates of sediment flux led to significant deltaic regression / progradation into the East Shetland Basin around this time and the development of the Ninian delta. Delta progradation took place in a lobate fashion, but the controls on avulsion remain unclear. Aggrading fluvial deposits probably overlie the delta. Abandonment of the Ninian delta was abrupt, and is likely to have occurred by in-place drowning.
Integration of the regional and small-scale observations suggests that sediment supply to the basin was a significant influence on the ultimate depositional architecture. Thus similar scale of base-level fall in the Forties, Sele and possibly Upper Balmoral sequences was accompanied by quite different depositional environments. Furthermore, peak regression in Forties was not accompanied by greatest sediment supply to the basin. Stark changes in sediment supply can be demonstrated in the Lower Balmoral sequence. The significant changes in sediment supply to the basin result in a very variable stratigraphy, and depositional sequences may not have a characteristic response on wireline logs. Small-scale sediment dispersal patterns were strongly controlled by the bathymetric relief of the basin. If base-level fluctuations influenced the evolution of the Ninian delta in the East Shetland Basin, it was at a level beyond seismic resolution, and as such, remains poorly constrained.

The sedimentary fill of the lower Paleogene of the North Sea records the lithospheric response to uplift of the margin of a failed-rift basin. Margin uplift is concomitant with the deposition of the depositional sequences, and it is suggested that the variation in sediment supply may tectonically-driven. On a more local scale, changes in fluvial drainage patterns during the Forties / Sele interval occur directly over the Bressay Granite, and contemporaneous with a change in the regional stress regime, from compressional to extensional. Sediment dispersal may therefore have been enhanced by local uplift of the Bressay Granite.
ACKNOWLEDGEMENTS

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The lower Paleogene of the Northern North Sea may remain a relatively understudied interval, but only because it was such an elusive body of sand to find. Along the circuitous route leading there, a number of fine souls accompanied me, and others manned roadside stalls, cheery and supportive, bearing standards and wielding erasers. Of course there was The Department Car (gold stars to Clare for the comfort, and Paul for the photos), and then - oh how I looked forward to it - the fieldwork. Some of the finest landfill sites I have ever visited (humour provided by Rolly Goldring & Sanjeev; subsistence by the Wards in Orpington), and the slap-stick continued in France (Fatty T. is doing well here). And then of course, the Great Leap Forward. Like it's occidental relative, it experienced some teething problems, but wise words from David Mudge, Jonathon Bujak, and Chris King amongst others directed me offshore, where I spent much of my remaining time. Fruitfully, I trust.

The emotional stability (or otherwise?) of Rachel, Sibs, Phil, Kettle, and latterly Ms D Ware (Amoco Personnel), Terri, and Fiona did a lot to improve the journey. I shall remember Rach's upside-down cakes with fondness. Lots of it seems quite fuzzy now (oh yes, and obviously a bonus point for Fuzz), but I remember jolly good times, so the quality of the entourage must have been pretty high.

Other foggy moments were ably navigated with the guidance of JU (Chief Compass Bearer), and Dick K for (Inspiration At The Right Moment). Richie made some fine corrections for magnetic North. The other Dick (Sutherland) & cohorts at the DTI coreshed were most helpful in letting me consult the data held by the DTI at Gilmerton. (It's touching to think of them looking safely after such important boxes of Paleocene sand.) The nit-picking of Debbie, Phil, Fiona, JT, Sarah et al. was invaluable.

Oh, so many fine memories. I particularly appreciated the support of my family over the years (Mr Lows down the road, to carry on the analogy). Others that spring to mind are Sally / Coleen / Paul / and someone else I forget at the moment for the best food fight I suppose I shall ever have. I am most certainly in debt to many others (the SSS Group, Oxonians everywhere, etc.), and they of course have my gratitude. Most importantly I must thank You, the Reader, for making my three years worthwhile & casting your eyes over this document.

This thesis was presented with the help of the letter 'F', and the grain size 'Coarse'.

Chapter 1

Introduction

1.1 Introduction & Geological Setting

The North Sea is a failed rift basin. The principal rifting phase occurred during the Triassic and Jurassic (Figure 1.1), and resulted in the tilted fault block topography associated with the early stages of mechanical rifting (McKenzie, 1978). The Triassic and Jurassic sediments were deposited in first continental, then marginal marine, and finally fully marine environments, reflecting the rapid subsidence within the grabens. Active rifting ceased at the end of the Jurassic throughout most of the basin - although faulting continued into the Cretaceous in the Northern North Sea - and the basin began its stage of post-rift thermal subsidence with the development of a classic steer's head geometry (Figure 1.1). The Cretaceous and early Paleocene of the North Sea are characterised by quiet-water chalk and marl deposition, with only very minor clastic input. At the end of the Cretaceous, the North Sea was thus dominated by three main grabens: the Central and Viking Grabens, and the Moray Firth. Two of these Jurassic structures continued to be significant structural elements in the East Shetland Basin until the Eocene epoch (Figure 1.2).

The post-rift, thermal subsidence phase of the North Sea rifting was interrupted in the early Tertiary by tectonic rejuvenation of areas immediately adjacent to the basin. To the northwest, a mantle plume impinged on the crust between Greenland and Norway (White, 1988; White & McKenzie, 1989), leading to the initiation of extension and then sea-floor spreading in the early Eocene (Figure 1.3). To the southeast, the Tethyan Ocean was
Figure 1.1. (a) Basin flank onlap of Dewey's (1982) classic steer's head basin may be caused by lithospheric flexure, lateral heat flow or heterogeneous stretching. After Chadwick (1985a). (b) Cross section of the northern North Sea showing the onlap of Tertiary sediments onto the basin flanks. After Condon (1988). (c) & (d) More detailed cross sections across the South Viking Graben and East Shetland Basin. The Paleocene is the oldest stratigraphy to onlap the main platform areas. After Glennie (1990).
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Figure 1. Isometric block diagram of the northern North Sea illustrating the differing structural development of the Unst Basin, the Viking Graben, the Stord Basin, and the Witch Ground Graben. From Glennie (1990).
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beginning to close, culminating in two main episodes of deformation in the Alpine region. The interaction of these two plate movements to the northwest and southeast of the North Sea was coincident with a fundamental change in the stress field over northwest Europe (Zeigler, 1987b; Figures 1.4a &b).

Although tectonic movements began in the Senonian (Zeigler, 1987b), significant uplift of the North Sea hinterlands did not result until the Danian, when reworked clastic and carbonate sediments are recorded in North Sea. These Danian sediments were removed from the platform areas and deposited throughout the Central and Northern North Sea (Knox et al., 1981; Johnson, 1987; Mudge & Bliss, 1983). The magnitude of uplift at this time is uncertain; the UK mainland was clearly uplifted (e.g. Green, 1989; Hillis et al., 1994; Brodie & White, 1994; Figure 1.5); Danian uplift was probably only limited in the Inner Moray Firth (Thomson, 1993; Hillis et al., 1994; Figure 1.6); and in the Northern North Sea any uplift is beyond the attainable resolution (Condon, 1988; Figure 1.7).

During the Late Paleocene, huge volumes of magmatic material were intruded into the crust along the line of the embryonic northeast Atlantic (White, 1988; Figure 1.8). Uplift was represented in the North Sea by the influx of clastic sediments, and large scale regression. These sediments in-filled the remnant topography resulting from the Jurassic extension (Figure 1.9). The Early Eocene regression preceded the onset of sea-floor spreading in the northeast Atlantic, but was contemporaneous with intrusive and extrusive volcanic activity in the British and Faeroe-Greenland Igneous Provinces (Enclosure 1). Jones & Milton (1994) estimated the magnitude of this uplift in the Outer Moray Firth as being in the order of 800m, on the basis of the basinward shift in coastal onlap as observed on seismic data. The culmination of this regression was coeval with the deposition of a deltaic succession (the Sele sequence) in the North Sea Basin (Enclosure 2). The regression was succeeded throughout the North Sea basin by significant transgression, marked by the deposition of a thick tuff, the Balder Formation. The Balder tuff occurs over a large area of NW Europe (e.g. Knox & Morton 1988; Figure 1.10), and probably coincided with the initiation of spreading in the northeast Atlantic (Andersen 1988; Hitchin & Ritchie, 1993), although sea-floor spreading may have started considerably later (e.g. Waagstein, 1988).
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Figure 1.10. Distribution of early Paleogene volcanoclastic sediments in NW Europe. (A) Phase 1 volcanoclastic sands. (B) Phase 1 airfall ashes. (C) Phase 2a airfall ashes. (D) Phase 2b airfall ashes. (E) Phases 2c and 2d airfall ashes. (F) Subphase 2b total ash thickness. Larger figures refer to ash thicknesses (in metres) in individual sections: suffix 'e' estimated from an incomplete section; suffix 'c' indicates contamination by detrital sediment. Contours show postulated thickness distribution with supposed effects of contamination and subaqueous redistribution removed. From Knox & Morton (1988).
Figure 1.11. Magnetostratigraphic-biostratigraphic correlations between the lower Paleogene deposits of the Hampshire-London Basin and the Paris Basin, showing the significant unconformities separating the onshore formations. From Aubry (1985).
Early Paleogene sediments preserved in the London / Paris and Hampshire basins also show the effects of base level changes around this time (e.g. Neal et. al, 1994; Knox et al., 1994). In these basins, marginal marine environments prevailed, and the stratigraphies of these areas are dominated by periods of non-deposition, or unconformity (e.g. Aubry, 1985; Figure 1.11). Balder equivalent tuffs are preserved in the transgressive London Clay Formation (C. King, pers. comm.).

1.2 Project Rationale & Aims

When the East Shetland basin was still a viable exploration target, regional studies were published which established the main depositional elements of the area (Heritier et al., 1979; Morton 1982; Mudge & Bliss, 1983), complementing work undertaken for the Central North Sea and Outer Moray Firth (e.g. Knox et al., 1981). However, the East Shetland Basin has not been encompassed by more recent publications reconsidering the detailed early Paleogene depositional environments in the light of seismic and sequence stratigraphic advances (e.g. Milton et al., 1990; Timbrell, 1993; Morton et al., 1993; Neal, 1994; Dixon et al., in press; Dixon & Pearce, in press; Milton & Dyce, in press). The regional controls on the Paleocene sediment dispersal in the East Shetland Basin are therefore relatively poorly documented, and this situation is rectified by this thesis.

The objective of the work was to apply techniques of seismic and sequence stratigraphy in order to understand the depositional architecture of the early Paleogene deposits in the East Shetland Basin. In order to most precisely describe the early Paleogene depositional environments, two in-depth studies were undertaken, around the Bressay area (UKCS block 3/28) and the Ninian field (UKCS blocks 3/3 and 3/8) (Figure 1.2). These two areas are representative of the marginal and basinal stratigraphies of the East Shetland Basin respectively. After examination of other datasets, the Bressay and Ninian areas were studied because they demonstrate some key aspects of the early Paleogene stratigraphy. Furthermore, this approach complements recent work refining the early Paleogene stratigraphy (e.g. Mudge & Copestake, 1992a & b; Armentrout et al., 1993; Den Hartog Jager et. al., 1993; Galloway et al., 1993; Neal et al., 1994), allowing this study of the East Shetland Basin to be set in the context of the North Sea as a whole.

The aims of this work were thus to compare and contrast the controls on sediment dispersal and preservation on the East Shetland Platform (the Bressay discovery and
environ), and in the East Shetland Basin (the Ninian field), particularly during the Forties / Sele sequence interval. This interval represents the most regressive episode in the early Paleogene and is the only period when the effects of changes in base-levels are apparent in the Northern North Sea. In completing this study, the objectives were to address a number of problems currently outstanding in the literature. These questions form the themes of the thesis, and are: the use of stratigraphic models (i.e. lithostratigraphy, sequence stratigraphy) in correlating the early Paleogene of the North Sea; the evolution of Sele deltaic depositional systems; and the role of tectonism in the deposition and preservation of strata in a post-rift basin.

1.3 Structure of the Thesis

Chapter one reviews the previous work and the present understanding of the early Paleogene systems of the North Sea, placing the study in its regional context. Chapter two goes on to describe the methodologies used in the thesis. Particular attention is given to the Graphic Correlation method, a powerful but little used method for biostratigraphic correlation.

Chapter three describes the stratigraphic framework evolved for this thesis, and outlines the regional work undertaken for the whole Northern North Sea. Chapters four and five present the results of the more detailed studies from the Ninian and Bressay areas. Chapter six reviews the work carried out in this thesis in the context of the North Sea generally, and presents the conclusions of the research.

1.4 Previous Work

Notes on nomenclature

Enclosure 3 summarises some of the stratigraphic schemes that have recently been proposed for the early Paleogene of the North Sea. This diagram underlines the fact that the existing lithostratigraphic terminology (as exemplified by the Mudge & Copestake stratigraphy) has been transferred for use in the sequence stratigraphic frameworks (e.g. Neal et al., 1994; Galloway et al., 1993; Den Hartog Jager et al., 1993), the details of which are dissimilar. The sequence stratigraphic approach rationalises the nomenclature by defining laterally equivalent sand and shale bodies within the same sequence. However, it
should be noted that lithostratigraphic formations may fall within the sequence of a different name (i.e. the Andrew Formation of Mudge & Copestake may be part of either the Andrew or Lower Balmoral Sequence of Neal et al.). In an effort to simplify these problems, this work principally followed the scheme of Neal et al. (1994). Enclosure 3 relates the published stratigraphic schemes to that of this thesis and will be referred to throughout the text.

In common with other authors, the term 'Paleocene' used in this thesis refers to the stratigraphic interval between the top chalk and the top of the Balder tuff. This stratigraphy is of uppermost Cretaceous to early Eocene age. Where prefixes are used to describe the Paleocene interval, this refers to either to relative age (e.g. late Paleocene) or chronostratigraphic age (e.g. Late Paleocene).

1.4.1 Stratigraphy

Parker (1975) first described the seismic stratigraphy of the base Paleocene to Balder Tuff interval in the central North Sea, describing a coastal 'deltaic' sequence, an argillaceous slope sequence, and a turbiditic basinal sequence. This framework was modified by Rochow (1981) who integrated the lithostratigraphic nomenclature of Deegan and Scull (1977) to define a threefold subdivision of the Montrose Group (Maureen, Andrew & Forties Formations) and a twofold subdivision of the 'deltaic' Moray Group (Sele & Balder Formations).

Subsequent publications developed separate stratigraphies for the Central North Sea (Knox et al., 1981), and Northern North Sea (Morton, 1982; Mudge & Bliss, 1983; Figure 1.12). These authors described the depositional environments in detail and the distribution of each mapped unit, which essentially comprised large, proximal sand bodies interfingering with basinal shales. A more detailed stratigraphic subdivision of these units was hindered by the lack of biostratigraphic control available in the extensive arenaceous formations (e.g. Berggren & Gradstein, 1981; King, 1982). This problem gave rise to different interpretations of the sand bodies in the basin, and thus contrasting
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<td>Phase 1</td>
<td>Lista / Andrew &amp; Maureen Formations (Unit 2a)</td>
<td>Lista / Andrew &amp; Maureen Formations (Unit 2a)</td>
</tr>
</tbody>
</table>

Figure 1.12. Correlation of the early regional stratigraphic frameworks for the Central North Sea (CNS) and Northern North Sea (NNS) (columns 1 to 4). Column 5: stratigraphies of Mudge & Copestake (1992a & b) and Mudge & Bujak (1994). Column 6: this thesis. Compare with Enclosure 3.
Figure 1.13. Isopach of comparable units (see Figure 1.12): Unit B of Morton (1982) and Unit 2a of Mudge & Bliss (1983). The sharp contrast in the mapped distribution of the sand body illustrates the difficulty in separating the Andrew / Lower Balmoral fan-apron. Note the different scales of the diagrams.
Figure 1.14. Diagrammatic cross-section of the early Paleogene near latitude 58°30′N, showing convergence of coal / toplap horizons, and erosion below the Sequence 8 coal. The coal horizons indicate tilting concomitant with subsidence of the margin uplift, i.e. the area of uplift narrowed whilst subsidence took place in the basin. From Milton et al. (1990).
Figure 1.15. (a) The long-duration relative sea-level cycle of Jones & Milton (1994) for the Outer Moray Firth, annotated to show the arrangement of sequence sets and 'composite systems tracts'. (b) Cartoon illustrating the geometry of sequence sets - 'sequence skewing' - during the long duration sea-level curve. See text for details.
paleogeographic interpretations for some depositional episodes (Figure 1.13). Improved biostratigraphic resolution has since updated these essentially lithostratigraphic interpretations of the stratigraphy (Isaksen & Tonstad, 1989; Mudge & Copestake, 1992a, b; Mudge & Bujak, 1994; Knox & Holloway, 1992), but biostratigraphic dating of the oldest clastic wedges (Maureen / Andrew Formations) in the Northern North Sea is of relatively low resolution (Mudge & Copestake, 1992b). The stratigraphy for the East Shetland Basin presented in this thesis improves the available resolution, and allows the basal Maureen / Andrew clastic wedges to be differentiated.

1.4.2 **Intrabasinal and extrabasinal tectonism**

Knox *et al.* (1981) first demonstrated the cyclic nature of the early Paleogene sequence, describing two regressive-transgressive trends of basin margin uplift and basinal subsidence within the Late Paleocene / Early Eocene period of uplift. This hinterland uplift was already associated with the opening of the northeast Atlantic (e.g. Bott, 1974; Hailwood *et al.*, 1979; White, 1988). Milton *et al.* (1990) described in detail the tilting of the basin margin in the Quad 14/15 area associated with this uplift, and which could be observed influencing the deposition of the Sele and Beauly Formations (Figure 1.14). Milton *et al.* also suggested in their paper that during uplift, basinal fan facies were predominantly deposited, whereas during the subsequent tilting/sinking phase, back-stepping shelf / shoreline systems dominated. This observation was supported by later work: Jones & Milton (1994) and Milton & Dyce (*in press*) demonstrated the change in architecture between their T30 & T40 sequences (deposited during uplift) and the T45 (stillstand) and T50 (sinking phase) sequences (Figure 1.15). This was termed sequence stacking by Jones & Milton. Similar effects were described by Neal (1994) - "nested cycles" - and Armentrout *et al.* (1993).

The marginal-marine facies preserved in the Moray Firth allow a direct estimation of base level, and Milton & Jones (1994) used this area to quantify the uplift and subsidence history of the Moray Firth using seismic stratigraphy. They estimated a base-level fall of over 800m and over 500m rise in the Late Paleocene (Enclosure 2). The only other area in the North Sea where base-level changes can be studied is on the East Shetland Platform (see chapter 5).
Figure 1.16. Chronostratigraphic diagram of Stewart (1987) for the lower Paleogene of the Central North Sea and Outer Moray Firth. The model comprises unconformity-bound sequences, however Milton et al. (1990) interpreted the stratigraphy to be bounded by condensed surfaces (see Figure 1.17). The ten-fold sequence division was examined by Neal et al. (1994) who concluded that sequences 4, 5, 6, 8 and 9 of Stewart (1987) were not discrete sequences in the Outer Moray Firth. See Enclosure 3 for correlation of Stewart (1987), Milton et al. (1990), Neal et al. (1994) and this study.
Figure 1.17. Chronostratigraphic diagram of Milton et al. (1990) for the lower Paleogene of the Outer Moray Firth. The interpretation depicts a series of sequences bound by surfaces of maximum condensation, in contrast to Stewart's unconformity-bound sequences (Figure 1.16). See Enclosure 3 for comparison with this study. Note the non-linear scale of the diagram.
In addition to regional uplift, rejuvenated intrabasinal tectonic activity has also been interpreted as occurring during the Late Paleocene in the North Sea. In particular, the abrupt change of facies across the western margins of the Viking Graben and East Shetland Basin during deposition of the Andrew / Lower Balmoral sequences has been attributed to fault movement (e.g. Heritier et al., 1979; Morton, 1982; Mudge & Bliss, 1983; Morton et al., 1993). This model of fault-controlled deposition was disputed by Condon (1988) and Bertram & Milton (1989), and is discussed further in chapter 6.

1.4.3 Alternative stratigraphic frameworks

Stewart (1987) was the first to apply seismic sequence stratigraphy to the Paleogene of the North Sea. Using seismic, well logs and detailed biostratigraphy, he divided the Paleogene into ten unconformity-bound seismic sequences (Figure 1.16). Stewart’s paper was important for three reasons: it combined high resolution biostratigraphy with seismic and well log analysis in a chronostratigraphic framework; it integrated marginward (proximal) and basinward (distal) lithostratigraphic units which had previously been separated; and it considerably refined the biostratigraphic resolution of the early Paleogene of the North Sea. Stewart’s work marked a return of interest to the early Paleogene in the North Sea, and realisation that subtle stratigraphic understanding was required to identify new Paleogene hydrocarbon plays.

Stewart’s work pre-dated the publication of the sequence stratigraphic model (e.g. Posamentier et al., 1988) and genetic sequence stratigraphy (Galloway, 1989a & b). Thus Stewart’s definition of unconformity-bound sequences (Figure 1.16), was only later amended by Milton et al. (1990), who showed that the boundaries of Stewart’s seismic sequences were in fact condensed sections (Figure 1.17). Subsequent to Stewart’s work, a number of publications have used a similar integrated approach to construct stratigraphies for the whole basin, with the result that there are now a number of different published sequence stratigraphic frameworks.

Den Hartog Jager et al. (1993) presented the highest resolution framework for the Central and Northern North Sea, defining nine sediment pulses into the basin in the Paleocene (Enclosure 3). They described an overall decrease in the volume and increase in ordering of the Paleogene depositional systems. The sequences of Den Hartog Jager et al. comprise shelfal erosion, concomitant with fan deposition downdip. Fan deposition in the basin was
interpreted as being separated by regionally correlatable shales. Similar to Knox et al. (1981) and Jones & Milton (1994), they recognised two regressive-transgressive cycles within the Late Paleocene. Den Hartog Jager et al. recognised the significance of tectonic uplift during this period on supplying the sediment to the basin. Galloway et al. (1993) also emphasised contemporaneous extra-basinal tectonic events and suggested that these events were influential in shaping the North Sea stratigraphy. The tectonosequence study of Galloway et al. (1993) is the lowest resolution of any of the stratigraphic frameworks.

In contrast to these two papers, Neal et al. (1994) used a database including the Central North Sea, Outer Moray Firth and the onshore Paleogene outcrops of NW Europe, and concluded that sea-level was a significant factor on the distribution of Paleogene depositional systems. Their stratigraphy defined eight depositional episodes between the Ekofisk sequence and the Balder sequence (inclusive) (Enclosure 3). Neal et al. tied their framework directly to a magnetochronostratigraphic timescale using magnetostratigraphic data available onshore (e.g. Townsend et al., 1985; Aubry, 1985; Aubry et al., 1986). This tie to the magnetochronostratigraphic timescale was important, as it allows direct comparison of the sedimentary fill of the North Sea Basin and the British and Faeroe-Greenland Igneous Provinces (Enclosure 1; see chapter 6). Neal et al. also emphasised the punctuated nature of the sedimentary fill, considering that individual sequences were bounded by composite unconformities / condensed sections. Neal et al. attained a high resolution subdivision of the Central North Sea stratigraphy using the Graphic Correlation method, which is also used in this study (see section 2.7).

Armentrout et al. (1993) constructed a regional stratigraphic framework for the Paleogene of the central and Northern North Sea. Armentrout et al. identified five cycles between the Ekofisk and the Balder, but emphasised the difficulty in correlating sand-prone facies in the basin. They considered that the boundaries to sequences in the basin were often composite condensed intervals. Their interpretation is similar to that of BP (e.g. Milton & Dyce, in press; Dixon & Pearce, in press), in defining five sequences over the same interval.

Following the work of Milton et al. (1990), the BP approach used flooding surfaces (gamma maxima) to define the boundaries of their (genetic) sequences, constraining this with a very high resolution biostratigraphic framework. The definition of the BP sequences on gamma maxima differentiates the BP approach from the others; most of the
frameworks utilise both sequence boundaries (*sensu* Exxon) and flooding surfaces to differentiate the stratigraphy.

The lithostratigraphic nomenclature of the basin has also been revised (Mudge & Copestake, 1992a & b; Isaksen & Tonstad, 1989; Mudge & Bujak, 1994; Knox & Holloway, 1994), generally incorporating some biostratigraphic control. The most detailed work, of Mudge & Copestake (1992a & b) and Mudge & Bujak (1994) is illustrated in Enclosure 3. In addition to purely lithostratigraphic criteria, Mudge & others used gamma maxima to subdivide the stratigraphy. When biostratigraphic control is poor or unavailable, these frameworks remain very practical tools for correlation in the Paleocene of the North Sea.

In addition to regional papers, more detailed studies have been published, particularly on the Paleogene of the Beryl Embayment (Morton *et al*., 1993; Timbrell, 1993; Newman *et al*., 1993; Jenssen, 1993; Dixon *et al*., *in press*; Dixon & Pearce, *in press*; Milton & Dyce, *in press*). These have detailed a number field-specific depositional and post-depositional styles of deep marine sands of Dornoch / Sele and Balder age, and are discussed below.

1.4.4 Recent work in the Northern North Sea

Dixon & Pearce (*in press*) describe the sequence stratigraphic evolution of the Quad 9 Viking Graben & Beryl Embayment area. As outlined above, Jones & Milton (1994) interpreted the Late Paleocene stratigraphy as having been deposited during a long duration sea-level rise associated with the development of the Icelandic hotspot. The BP sequences T30 (equivalent to the Lower and Upper Balmoral sequences of this thesis) & T40 (approximately equivalent to the Forties herein) were deposited during relative sea-level fall; T45 during stillstand (Sele); and T50 (Balder) during subsequent rise (Dixon *et al*., *in press*; Dixon & Pearce, *in press*; Milton & Dyce, *in press*). Milton & Dyce (*in press*) described topset aggradation in the T45 interval (i.e. implying a relative sea-level rise), followed by a series of downstepping deltaic sequences, each deposited successively more basinward than the last (Figure 1.18). The stranded coastal systems left during this relative base level fall were bounded at the top and base by unconformities and/or a basinward
Figure 1.18. Block diagrams showing the schematic evolution of the Beryl Embayment (after Dixon et al., in press). BP sequences T46 and T48 are approximately equivalent to the lower and upper Sele sequences of this study respectively (see Figure 5.4 for correlation). Note the incision around the Bressay area as base-level dropped.
shift in facies (i.e. were deposited during a forced regression, N. Milton pers. comm.). These stranded sequences were termed Midstand Systems Tracts by Milton & Dyce (in press). This work is discussed in more detail in the Bressay chapter (chapter 5).

The publications on the Beryl Embayment area differ slightly on the interpretation of the Late Paleocene sequences. Mudge & Copestake (1992b) claimed that the Forties sequence of the Outer Moray Firth is represented by a condensed section in the Northern North Sea. Dixon et al. (in press) also observed little deposition in the basin, but described delta progradation on the margins of the Beryl Embayment. Timbrell (1993) viewed the base of the Sele as a time of incision during rapid relative sea-level fall (Figure 2 of Timbrell, 1993) (i.e. a type 1 unconformity), and the Sele sands as being basin floor sands. Dixon & Pearce (in press) described relative sea-level continuing to fall throughout their T46 and T48 sequences.

The systems tracts interpretation of the Sele and Balder sequences of Newman et al. (1993), Timbrell (1993), and of BP also vary. Newman et al. (1993) viewed the Balder and Frigg intervals as part of the same lowstand system tract, whereas Timbrell (1993) separated the two intervals into separate sequences. In contrast, Milton & Dyce (in press) described their Balder sequence (T50) as a highstand interval. The interpretation of systems tracts in the Paleocene of the East Shetland Basin is discussed in section 6.2.3.

1.5 Context

This work has been undertaken at a time of revived academic and industrial interest in the lower Paleogene of the North Sea, particularly in the south Viking Graben area. Seven different stratigraphic frameworks have been published since the inception of the project (Mudge & Copestake, 1992a & b, plus Mudge & Bujak, 1994; Armentrout et al., 1993; Galloway et al., 1993; Den Hartog Jager et al., 1993; Neal et al., 1994; Knox & Holloway, 1994; the BP stratigraphy), most of which cover the entire Paleogene depositional system (spatially and temporally). In addition, a considerable number of papers have been published on the Beryl Embayment and surrounding areas. Against this background, the objectives of this work have been to understand the Late Paleocene sedimentary evolution of a relatively understudied area - the East Shetland Basin - and to contrast the findings with those for other basins. This work falls between the scale of the
two sets of publications, and describes in detail the evolution of lower Paleogene depositional systems.

In this study, a number of problems in the literature were addressed. These were:

a) Unification of the published lithostratigraphic and sequence stratigraphic North Sea Paleogene frameworks. Significant differences occur between sequence stratigraphic frameworks (e.g. Armentrout et al., 1993 versus Den Hartog Jager et al., 1993) and between approaches (e.g. Mudge & Copestake, 1992a versus Neal et al., 1994). The utility of these frameworks was considered by examining the nature of the correlation surfaces used, and the efficacy of these surfaces in correlation.

b) The evolution of the Sele deltaic depositional systems is not well described in the previous literature, and this situation is redressed here. In addition, some consideration is given to the development and preservation of the delta during progradation.

c) The assessment of the role of tectonism in the deposition and preservation of strata in the North Sea varies in published literature. This question is examined on both a local and basin-wide scale in this work.
Chapter 2

Data & Methodology

2.1 Introduction

This chapter describes the database amassed for this project, and introduces the seismic and stratigraphic techniques that were used. The relatively unknown Graphic Correlation Method used for biostratigraphic correlation is discussed in some detail in the final section. Otherwise, the discussion of the methodologies is in the context of their use herein, and is not intended to be exhaustive. Reference is made to the original work throughout.

The data used in this Paleocene study were obtained in the course of hydrocarbon exploration, in the period 1969-1990. The main exploration targets in the Northern North Sea were of Jurassic age. Although major discoveries had been made in the Paleocene of the Central North Sea (e.g. Forties), the Paleocene has traditionally been considered to be a secondary target. No economic discoveries were made in the Paleocene north of Bressay (Figure 2.1a), and the Paleocene soon ceased to be an exploration objective in the East Shetland Basin. As a consequence, the well log and biostratigraphic data available over the Paleocene interval is predominantly of 1970's vintage, and little has been published on the area with the exception of regional reviews by Morton (1982), Mudge & Bliss (1983), Condon (1988), Mudge & Copestake (1992b), Knox & Holloway (1992) and Den Hartog Jager et al. (1993).

2.2 Seismic Data

A total of 4150km of 2D regional seisimic and two 3D surveys were integrated for this work (Figure 2.1b). The 2D seismic data from the East Shetland Basin was designed
Figure 2.1a. Seismic data in Northern North Sea as used in this thesis. The location of the two Ninian 3D seismic grids (Chapter 3) is shown; the left inset shows the seismic grid over the Bressay Area (Chapter 5).
Figure 2.1b. Hydrocarbon discoveries in the Tertiary of the North Sea. Note that Bressay is the only Tertiary oil discovery in the study area.
to image targets of Jurassic age, and consequently the quality of such data over the Paleocene interval was not high. The incorporation of 3D seismic data ameliorated this situation, allowing high resolution work to be carried out in two strategic areas (UKCS blocks 3/3 and 3/8).

The spacing of the 3D seismic data in the Ninian field (12.5 metres) was approximately 1000 times more dense than the 2D seismic data. The area of 3D seismic coverage also included the highest density of well data (23 wells in 2 blocks). This concentration of well and seismic data allowed the development of a detailed seismic and stratigraphic model for the Ninian area, which was representative of basinal depositional settings. For the second detailed study area, the Bressay area, a higher density seismic and well dataset was similarly obtained (Figure 2.1a).

### 2.3 Well Data

A total of 158 wells were examined from the Northern North Sea, using composite logs (all wells), density-neutron logs (approximately 20% of wells), and dip logs (approximately 20% of wells) as available. The sparse core data was used to calibrate the electric logs where available. Biostratigraphic data coverage was predominantly in the SW of the study area (south East Shetland Basin and the Bressay area). The data used thus was:

<table>
<thead>
<tr>
<th>Total number of wells in study</th>
<th>158</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Held</strong></td>
<td>109</td>
</tr>
<tr>
<td><strong>Examined on microfiche</strong></td>
<td>49</td>
</tr>
<tr>
<td>Core</td>
<td>2/10a-6</td>
</tr>
<tr>
<td></td>
<td>2/10a-7</td>
</tr>
<tr>
<td></td>
<td>211/29-1</td>
</tr>
<tr>
<td></td>
<td>3/3-11</td>
</tr>
<tr>
<td>Biostratigraphy</td>
<td>32 wells (13 of high quality)</td>
</tr>
</tbody>
</table>

Thus well log and seismic data dominate, with variable biostratigraphic or sedimentological corroboration.
Maximum Interference  No Interference

Decreasing Amplitude

Reflection from top limestone

Reflection from base limestone

No reflection below 1/30 wavelength (complete interference)

1/4 wavelength

1/2 wavelength (50m)

50 Hz Wavelength

Shale 3000 m/s

Limestone 5000 m/s

Shale 3000 m/s

Figure 2.2. Interference effects associated with decreasing bed thickness (adapted from Badley, 1989). The limestone must be greater than half the seismic wavelength for no interference; maximum interference & amplitude of the resulting reflection occurs at a limestone thickness equivalent to 1/4 seismic wavelength.
Figure 2.3. The Fresnel Zone: minimum resolution of seismic data in the horizontal plane (adapted from Badley, 1992). The size of the Fresnel Zone constrains the minimum horizontal resolution observed on 2D or 3D seismic.

\[
R_f = \frac{\text{Velocity (average)}}{2} \times \left( \frac{\text{TWT}}{\text{dominant frequency}} \right)^{1/2}
\]
54 wells were tied to seismic data using velocity logs or seismic calibration logs. The fit to known reflectors was always good, and there was no reason to suppose that the ties were not accurate at this relatively shallow level.

### 2.4 Data Resolution

The exploration tools used in this study - reflection seismic, well logs, and biostratigraphy - each investigate the subsurface geology in fundamentally different ways. The resolution of each technique is controlled by a range of factors, which can be separated into two categories:

1) the physical limits of resolution
2) imposed sampling limits

For **seismic** data, the physical limit of resolution is a function of the large size of the seismic waveform with respect to the thickness of the investigated bedforms. Wave interference limits the vertical resolution of the seismic data: interference occurs when bed thicknesses are below half the thickness of the seismic waveform; beds below 1/4 the thickness of the seismic waveform are not resolved (e.g. Meckel et al., 1977; Figure 2.2). The minimum horizontal seismic resolution is limited by the 'Fresnel zone' (e.g. Lindsey, 1989; Figure 2.3). The imposed sampling limits of seismic data depend on the designs of the source and receiving arrays. In most cases, the seismic used in this study was shot for Jurassic targets. The resolution of these surveys at Paleocene level was poor because the high frequency content was removed from the data during processing for Jurassic targets.

The level of detail that can be obtained from both 3D surveys and digital 2D surveys (the SOV-812 and UK-85 surveys in block 3/28) when examined on a workstation is of a higher definition than conventional paper 2D data, in both vertical and horizontal directions. This is due to the colour enhancement of the data, and the fact that the data can be manipulated (e.g. rescaled, flattened on a horizon, or the gain altered) although the actual resolution of the data is not increased. GeoQuest software was used for seismic interpretation.
The accuracy of *biostratigraphic* data is ultimately constrained by the rates of evolution of the preserved fauna and flora. In the Paleocene of the North Sea, the low diversity of faunal assemblages allows only relatively poor resolution. This is primarily due to the high sedimentation rates during deposition of the Montrose Group and the anoxicity of the basin during deposition of the Moray Group. The imposed limit on resolution of Paleocene data was the sparse and irregular sampling, and the poor identification of the biota in older wells. Contractor reports varied greatly in quality.

The physical resolution of *well logs* obtained varied with the tool. In most cases, the resolution of the tool is limited by the physical spacing of the sensors in the downhole tool. Improved resolution could be obtained, but is of little interest to most oil companies given the much lower resolution of other forms of data which well log data is compared. In the study, the approximate minimum resolutions are listed in Table 2.1.

Table 2.1. The minimum resolution of well logs is an order of magnitude greater than other data types

<table>
<thead>
<tr>
<th>Data</th>
<th>Resolution</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Seismic</strong></td>
<td>$(\frac{1}{4}\text{ wavelength})$</td>
<td>Frequency 40Hz, velocity 4000 ft/sec</td>
</tr>
<tr>
<td>3D at 2 seconds TWT</td>
<td>= 40'</td>
<td></td>
</tr>
<tr>
<td>2D at 1 second TWT</td>
<td>= 25'</td>
<td></td>
</tr>
<tr>
<td><strong>Biostratigraphy</strong></td>
<td>± 30'</td>
<td>Sampling limit</td>
</tr>
<tr>
<td><strong>Well logs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gamma</td>
<td>3'</td>
<td>Tool limit in ideal conditions</td>
</tr>
<tr>
<td>Sonic</td>
<td>2'</td>
<td>Tool limit in ideal conditions</td>
</tr>
<tr>
<td>Density</td>
<td>2'</td>
<td>Tool limit in ideal conditions</td>
</tr>
<tr>
<td>Resistivity</td>
<td>4'</td>
<td>Tool limit in ideal conditions</td>
</tr>
</tbody>
</table>

2.5 **Introduction to Seismic Stratigraphy**

In the 1960's and 1970's, technology became available to produce seismic reflection profiles of sufficient quality for their utilisation in hydrocarbon exploration. The methodology of seismic stratigraphy evolved contemporaneously with the acquisition and use of more sophisticated seismic profiling (particularly for hydrocarbon
Figure 2.4. Stratal termination observed at depositional sequence boundaries (after Mitchum et. al., 1977). The geometry of the reflector terminations is used to define the nature of the sequence boundary. For explanation see text, section 2.5.
exploration), and the development of depositional process models from Holocene studies (Brown & Fisher, 1977).

The seismic stratigraphic method (Payton, 1977) is a geometric methodology which groups subparallel or parallel seismic reflectors into packages, bound by surfaces of reflector termination. Mitchum et al. (1977) argued that the sequences were internally "genetically related" (i.e. seismically conformable), although this does not preclude breaks in sedimentation occurring beyond seismic resolution. The seismic sequence boundaries represent significant changes in the basin fill architecture, and by implication, significant changes in depositional environments in the basin: unconformities and their correlative conformities (Mitchum et al., 1977) or hiati. Sequence boundaries are characterised on seismic sections by the geometry of the strata terminating against them. There are 6 possible geometries of four different types (Figure 2.4; explanations from Mitchum et al., 1977):

**Truncation**  
Erosional truncation (Figure 2.4a) is defined as being when strata are terminated by erosion at the upper boundary of a depositional sequence. This may be locally, as in a channel, or regionally. Structural truncation: is truncation by any other method: faulting, slides, salt movement, or igneous intrusion, although it may be difficult to differentiate between the two types.

**Toplap**  
An upward termination of initially inclined strata (Figure 2.4b). Toplap indicates a non-depositional hiatus, when depositional base level was too low to permit strata to extend further updip. Toplap commonly occurs in deltas, and is considered in detail in this study, particularly in chapter 4.

**Baselap**  
Termination of strata at the lower boundary of a depositional sequence. Onlap occurs when initially horizontal or low angle strata abut against a surface of greater inclination (Figure 2.4d); downlap occurs when an initially inclined surface terminates against a surface of lower initial inclination (Figure 2.4e). Onlap can be further separated into marine onlap and coastal onlap, where coastal onlap occurs in a landward direction. Coastal onlap is used in this study as a indicator of relative sea-level; it relies on the clear identification of a topset or similar 'zero datum'.

**Concordance**  
The seismic reflectors underlying and overlying the boundary are parallel (Figure 2.4c & f).
The foundations of the seismic stratigraphic principles and method were first published in AAPG Memoir 26 (Payton, 1977). The fundamental assumption of the model was introduced in Vail et al. (1977a): that in nature "there is no continuous physical surface that follows the top of a time-transgressive unit [i.e. lithostratigraphic unit]". That is, seismic reflections do not cross depositional time-lines. Vail et al. claimed that this is true of reflections from both conformable strata and unconformities. This assumption, key to the seismic stratigraphic interpretation method used in this study, is considered below.

The above argument of Vail et al. had its roots in Campbell (1967), who defined a bedset as "a composite of repetitive, similar beds, bounded above and below by bedset surfaces". These bedset surfaces separate beds of different lithology. The upper and lower surfaces of the bedset - the depositional surfaces - are synchronous with the upper and lower bedding surfaces, which between them define a time-stratigraphic unit of finite (but geologically very short) duration. However, whereas a bedding surface is laterally discontinuous with a change of facies, the depositional surface still exists, even though it may lose its physical expression. Thus, the depositional surface is a laterally continuous, effectively isochronous surface.

Vail et al. (1977a) considered that at the seismic scale, seismic reflections would follow this isochronous depositional surface, because they reasoned that depositional surfaces mark the largest acoustic impedance contrasts in a given seismic section. Thus a seismic reflector would register a lateral facies change by a different reflection character, but could not cross the depositional time-lines, the depositional surfaces. Accepting this premise means accepting that seismic correlations are, uniquely, chronostratigraphic. This has been challenged in principle by the modelling of Tipper (1993) who demonstrated that it is possible for seismic reflections to follow lithostratigraphic boundaries. Aubry (1993) supported this contention using very high resolution biostratigraphy, but Aubry's approach was too detailed to be replicated here.

Vail et al. extended their assumption to unconformities, arguing that all deposition below an unconformity pre-dated all deposition overlying it. This has been shown to be invalid generalisation (e.g. a transgressive ravinement unconformity, Swift, 1968; Cartwright et al., 1993), but in cases where the generalisation holds, sequence boundaries remain an important correlative tool.
(A) Exxon Sequence Stratigraphic Model

(B) Armentrout et al. (1993) for the North Sea

Dip extent penetrated in Paleocene of the ESB

bft: basin floor thick of LST; HST: highstand systems tract; LST/pc: lowstand systems tract / prograding complex; mfs: maximum flooding surface; SB: sequence boundary; sft: slope front thick of LST; SMST: shelf margin systems tract; TS: transgressive surface; TST: transgressive systems tract.

Figure 2.5. Depositional dip sections of (A) the sequence stratigraphic model (Posamentier & Vail, 1988) and (B) as adapted by Armentrout et al. (1993) for the North Sea, illustrating the conceptual relationships between a sequence, and its comprising systems tracts and bounding surfaces. The box in (B) schematically represents the dip extent penetrated by wells in the study area, with the shelf break in this case being represented by the structural break of the East Shetland Platform. Thus the updip limit represents the position of Bressay, the downdip position the Ninian field.
Figure 2.6. Generalised stratigraphic (A) & chronostratigraphic (B) sections of a depositional sequence, from Mitchum et. al. (1977). Vertical scales are depth & time respectively. Note that at a well log scale of investigation, hiatuses might exist between individual reflectors. Thus the lower hiatus may be continuous.
2.6 Well Log Correlation

Lithostratigraphy uses the physical characteristics of a stratal succession to subdivide rock units. A lithostratigraphic correlation draws upon both an objective description of the rocks (and particularly their petrophysical properties in subsurface correlations), and combines this with an understanding of facies models to interpret the vertical succession. Lithostratigraphic correlations therefore rely on intrinsic rock properties, together with models of extrinsic factors, constructed from modern and ancient depositional analogues. In the subsurface where good facies models are hindered because of poor lateral control, lithostratigraphic correlations can be poor, but this situation can be improved when combined with the introduction of some chronostratigraphic control (biostratigraphy in the case of this study).

Sequence stratigraphy (Vail, 1987; Posamentier & Vail, 1988a; Posamentier et al., 1988; Van Wagoner et al., 1990) was introduced partly as a way of addressing the problems of scale and resolution in well log stratigraphy. Unlike lithostratigraphy, sequence stratigraphy is both a methodology and a model. The methodology differs from lithostratigraphy in the emphasis sequence stratigraphy places on the bounding surfaces to stratigraphic packages. Sequence stratigraphy highlights the depositional discontinuities and hiatus in a succession, which can help predict lateral changes. The sequence stratigraphic method can in this way improve the predictive power of depositional models. However, both sequence stratigraphic and lithostratigraphic methods require biostratigraphic data to constrain possible interpretations.

The depositional bounding surfaces which are most frequently used in sequence stratigraphy are the sequence boundary (an unconformity and its correlative conformity); the maximum flooding surface (MFS), which represents the time of maximum transgression onto land, and a condensed interval in the basin; and the transgressive surface (TS) (Figure 2.5). The authors of the original sequence stratigraphic model considered sequence boundaries (unconformities) to be the principal surface for defining sequences. Thus Mitchum et al. (1977) defined a depositional sequence as "a relatively conformable succession of genetically related strata bounded at its top and base by unconformities or their correlative conformities" (Figure 2.6). This largely objective definition was expanded to incorporate the idea that a sequence is "composed of a succession of systems tracts and is interpreted to be deposited between eustatic fall inflexion points" (Posamentier et al., 1988). The term now has both a methodological and a model connotation.
Figure 2.7. Schematic comparison of the Exxon Depositional Sequence and Galloway Genetic Stratigraphic sequence definitions. The Exxon Depositional Sequence (Posamentier & Vail, 1988) is bounded by sequence boundaries (SB), or basinward shifts in facies, and includes an implied subdivision of the sequence into systems tracts (LST, TST, HST). In the Galloway model, a sequence is bounded by maximum flooding surfaces (mfs's), and is subdivided by means of stacking patterns (Underhill & Partington, 1993b). In the deep marine environment, correlation of these boundaries may not be simple, and a composite approach was taken in this study. See also chapter 6.
The rationale for using unconformities to define sequences was twofold (Posamentier and James, 1993): (a) an unconformity represents a surface separating two internally continuous packages; and (b) unconformities can be of economic significance. In contrast, Galloway (1989a, b) suggested that sequences should be defined by maximum flooding surfaces (MFS's), arguing that these MFS's represented times of paleogeographic change (Figure 2.7). This approach was supported by Underhill & Partington (1993b), who considered that MFS’s were more recognisable than unconformities using wireline logs alone. This study did not exclusively use the approach of one or other model; the approach used is reviewed in section 6.2.

An important aspect of 'Exxonian' sequence stratigraphy is that sequences are further subdivided in the sequence stratigraphic model by the identification of parasequences, and the stacking of these parasequences into characteristic parasequence sets which allow the definition of systems tracts (Figures 2.5 & 2.7). A parasequence is defined as "a relatively conformable succession of genetically related beds or bedsets bounded by marine flooding surfaces and their correlative surfaces" (Van Wagoner, 1985), and it has no explicit model connotation. Parasequence sets are defined as "a succession of genetically related parasequences that form a distinctive stacking pattern" (Van Wagoner, 1985). These combine to form systems tracts, although the term is purely descriptive (Posamentier & James, 1993).

The meaning of systems tracts, like sequences, has also evolved. Brown and Fisher (1977) first stated that “contemporaneous depositional systems can be linked to produce...a systems tract”. Posamentier et al. (1988) altered this definition, arguing that systems tracts are the building blocks of sequences: systems tracts are thus composed of parasequence sets, and defined by the stacking patterns within these sets. Systems tracts "explicitly involve interpretations regarding sea-level change", “although they are not defined of the basis of this association” (Posamentier & James, 1993; Posamentier et al., 1988). Their use in this study in considered in section 6.2.

The use of the original sequence stratigraphic model, and its refinements (Posamentier et al., 1988; Posamentier & Vail, 1988; Van Wagoner, 1990; Posamentier & James, 1993) have generated much discussion (e.g. Miall, 1986 & 1992; Galloway, 1989a, b; Walker, 1990). Particular criticism has been directed at the linking of the model to the eustatic sea-level curve of Haq et al. (1988). For instance, Miall (1992) demonstrated that the detail of the Haq. et al. (1988) curve is so great compared to the resolution of the available biostratigraphic data, that miscorrelations or bogus correlations are
probable (Figure 2.8). Underhill (1991) argued that use of the Haq. et al. curve in
tectonically active depositional settings is inappropriate, as local effects overcoming
any eustatic effects could be misinterpreted as being of more regional significance.
This case can be argued as being relevant to the Paleocene of the North Sea, and is
discussed in chapter 6.

2.7 Biostratigraphic Data & Methodology

2.7.1 Data

The biostratigraphic data used in this project were obtained from contractor
biostratigraphic reports provided by numerous companies, particularly Oryx (UK)
Energy Company, Ninian Operating Partnership (Chevron, Oryx, Ranger, Murphy,
Sun and Neste), Amoco (UK) Exploration Company, Sovereign and Conoco. The
quality varied enormously between contractors, and was generally poorer in older
wells. A total of 32 reports were used in the study of the East Shetland Basin. A
minimum of 4 closely spaced points was preferred to define graphic correlation
terraces (see Figure 2.9) in each well.

Individual species range data was extracted from this database for taxa which were
considered to be stratigraphically important. A choice of 89 taxa was made over the
base Paleocene to top Balder interval, after reference to numerous published and
unpublished reports (e.g. Dixon & Pearce, in press; Haq et al., 1988; King, 1982;
Knox et al., 1981; Knox & Holloway, 1992; Mudge & Copestake, 1992a & b; Mudge
& Bujak, 1994; Neal et al., 1994; Neal, 1994; Schroeder, 1992; Stewart, 1987). The
compiled data consisted of depth occurrences for first downhole occurrences (FDO's),
extinctions or tops; last downhole occurrences (LDO's), or bases; and first downhole
acme occurrences (FDAO's), or acmes. Species range charts were used where
possible.

2.7.2 Previous Work & Methodologies

Subsurface biostratigraphy generally uses single or multiple biostratigraphic events to
represent effectively isochronous surfaces in correlation (taking into account sampling
factors - see section 2.4). This biostratigraphic method has been used in all the existing
Paleogene publications, with the exception of Neal et al. (1994a), and O'Connor &
Figure 2.8. Correlation of random data with the global cycle chart of Haq et al. (1988) (after Miall, 1992). Correlation of the 4 synthetic sections (1 to 4) with the cycle chart produced successful correlation at least 77% of the time. Thus with an increasing number of sequences in any succession, correlation with a eustatic sea-level chart will rise whether the correlations are correct or not.
Figure 2.9. Cartoon of the Graphic Correlation method. (a) Ranges of taxa plotted against the scaled composite section for the basin; (b) depth occurrences of taxa plotted against well log; (c) depth versus time correlation. See section 2.7 for details. From Neal et al. (1994).
Figure 2.10. Wells used in the construction of the composite section for the Paleocene of the North Sea. The distribution of the wells reflects the main depocentres of the Paleocene interval. Courtesy of Amoco (UK) Exploration Company.
Walker (1993). However, the biostratigraphic framework of the North Sea was only poorly understood during early exploration, and the biostratigraphic resolution of the Paleocene stratigraphy has improved significantly since the late 1980's (particularly since Stewart, 1987). Biostratigraphy subsequently became an important tool for subdividing the stratigraphy, both in lithostratigraphic (e.g. Mudge & Copestake, 1992a,b; Knox & Holloway, 1992) and sequence stratigraphic studies (e.g. Den Hartog Jager et al., 1993; Neal et al., 1994). Recent publications have used a number of different approaches to biostratigraphic definition: key markers and/or assemblages (e.g. Morton, 1994; Mudge & Bujak, 1994; Dixon & Pearce, in press; Dixon et al., in press) or zonal systems (e.g. Vining et al., 1993; Den Hartog Jager et al., 1993; Timbrell, 1993). The most serious drawback of the recent publications is their dependency on unpublished or contractor frameworks (which limits their use in other studies), or their use of rare species which leads to problems in taxonomic identification (Neal et al., 1994).

The differences between the various biostratigraphic frameworks are partly due to the isolation of the North Sea basin in the late Paleocene, and the absence and/or non-preservation of reliable pelagic (i.e. non facies-controlled) marker species. Many North Sea taxa, particularly foraminifera, have relatively limited, environmentally-controlled occurrences that do not match their maximum, world-wide ranges. The improving quality of the Paleocene biostratigraphy through the 1980's and 1990's reflects the improved definition of basin-specific species ranges, but over the Forties, Sele & Balder intervals, the situation is still poor. The key biostratigraphic markers used over these intervals are predominantly palynofloral FDAO's, which are particularly difficult to characterise in subsurface wells with only poor sampling. This is highlighted by the variation in the order of species tops - not just ranges - identified by different authors (e.g. Neal et al., 1994 and Mudge & Bujak, 1994), indicating that the reliability of biostratigraphic markers is in many cases poor.

2.7.3 Introduction to the Graphic Correlation Method

The graphic correlation method (Shaw, 1964; Neal et al., 1994) is a powerful tool for subdividing the stratigraphic fill of basins, and was applied to the Northern North Sea basin in order to more precisely understand the evolution of the Paleocene sedimentary distribution. The methodology and its application in this study are described below. The results of the work are discussed more fully in chapter 3.
The graphic correlation method scales the occurrence of all biostratigraphic events against a paradigm complete section for that basin. The graphic correlation method incorporates the ranges of all available taxa (benthic and planktic foraminifera, diatoms, radiolarians, calcareous nannoplankton and palynomorphs in the case used here), and cross-plots their depth occurrences against the composite section (Figure 2.9). As depth occurrences are plotted against a time scale, the graphic correlation method has particular strengths:

1) it can be used to quantify relative depositional rates,
2) it allows the identification and correlation of hiatal intervals (Neal et al., 1994)
2) extended / reworked and depressed / caved biostratigraphic markers can be identified

Construction of the Composite Standard Section

The composite standard used in this study was constructed in 1991 by J. Stein & J. Gamber of Amoco Production Company, using 35 key wells from the Outer Moray Firth and Viking Graben area (Figure 2.10). The methodology used in constructing the composite section is described in detail in Stein et al. (in press), but essentially involved identifying the most complete well sections from the principal depocentres (to avoid a sampling bias). The chosen sections are then integrated into one paradigm section (the 'composite standard'), which represents the maximum possible depositional thickness in the basin. The composite standard was then tied against a magnetochronostratigraphic timescale (Haq et al., 1988 in this case), which allows individual bioevents to be assigned values (Composite Standard Units, or CSUs) representing their relative position against the composite standard (complete section) for the basin. CSU values thus represent a relative, quasi-linear timescale. The values are quasi-linear as the composite standard may itself be incomplete, in addition to the continuing redefinition of the magnetostratigraphic timescale (e.g. Berggren et al., 1985; Haq et al., 1988; Harland et al., 1990; Cande & Kent, 1992). However, the CSU timescale was believed to be almost complete in this case, and was assumed to be so for practical purposes.

The work of Neal et al. (1994) used the same original database as in the Stein & Gamber study, but the two pieces of work evolved independently, and were tied to different timescales. In addition, Neal et al. used data from onshore NW Europe to further refine their basin stratigraphy. Thus the assigned CSU values differ, and other
Figure 2.11. Cartoon demonstrating the simplified interpretation of the Graphic Correlation method (solid line) & the probable real-life scenario plotted from core data. Biostratigraphic data is plotted with error bars as if samples were from cuttings, as with the data used in this study. After Neal et al. (1994).
differences exist between the two frameworks. The framework used here was calibrated against other published biostratigraphic schemes (Dixon & Pearce, in press; King, 1982; Knox et al., 1981; Knox & Holloway, 1992; Mudge & Copestake, 1992a & b; Mudge & Bujak, 1994; Neal, 1994; Stewart, 1987).

2.7.4 **Use of the Graphic Correlation Method**

In the Graphic Correlation Method the depth occurrences of reported taxa (y-axis) are cross-plotted against their assigned CSU values on the x-axis (Figure 2.9c). The points on the graph represent the relative accumulation rate (depth versus relative time) of the section, ignoring the effects of compaction. A line of correlation (LOC; Neal et al., 1994) is then drawn to honour the maximum number of data points. Figure 2.9 shows that the LOC comprises straight line segments which are either steeply sloping (representing the relative sedimentation rate over the interval as indicated by the preserved fossils), or sub-horizontal 'terraces'. A 'terrace' is a Graphic Correlation Method term, but geologically it represents a hiatal interval (Neal et al., 1994), the interpretation of which is dependent on the depositional setting. Figure 2.9 illustrates that occurrences of taxa off the LOC are extended (reworked) or depressed (caved), although with real data, the process of deciding which events are 'real' and which 'false' can be very subjective.

Figure 2.11 examines a hiatal interval or terrace in more detail. The diagram illustrates that the available data resolution does not allow a precise definition of the surface to be made. Sample gaps can extend the interpreted length of a data terrace, a problem commonly encountered in this work (e.g. defining the youngest age of the Lower Balmoral sequence). Definition of the periods of common sedimentation in the data was thus only undertaken with wells with high density, good quality data over the particular intervals.

2.7.5 **Biostratigraphic framework used in this study**

The Graphic Correlation Method was applied to the available biostratigraphic data in this project on a well by well basis. The resulting LOCs were then superimposed to establish any periods of sedimentation common to all the wells (Enclosure 4). The result was a biostratigraphically defined depositional framework for the East Shetland Basin. This framework defined seven depositional episodes for the basin, which was correlated against other biostratigraphic frameworks for the North Sea (Enclosure 3).
The variation of individual wells within this framework is examined in the subsequent chapters.

The error in defining each depositional episode was minimised by only using wells with highest quality biostratigraphic data over the specific interval to define each episode, although there is a minimum +/- 30' depth error associated with sample collection. The final framework only used depositional ranges which were well constrained: where data constraining individual episodes was ambiguous, or unsupported, the data was not used. The indicated duration of the depositional episodes is therefore probably the maximum. Correspondence with the biostratigraphic schemes of other authors is high, so errors are likely to be in the order of +/- 500,000 years normally associated with biostratigraphic data. However, internal consistency in areas of high data density could conceivably have higher resolution.

The sequences are described in detail in section 3.4, but the data resolution was poorest for the Lower Balmoral sequence. Comparison with other biostratigraphic schemes highlights different interpretations of biostratigraphic FDAs and LDAs, particularly in the Forties / Sele interval: detailed comparisons between the schemes are probably not accurate over these intervals.
Chapter 3
The East Shetland Basin

3.1 Introduction

This chapter outlines the depositional framework developed for the Northern North Sea, and presents the results of regional well and seismic mapping of the area. The chapter sets the context for the more detailed studies of the Ninian and Bressay areas (chapters 4 and 5; Figure 3.1) where seismic and well coverage was of a higher density. The results of all three chapters are integrated in chapter 6, where the main discussion of the data occurs. The broader context of the Northern North Sea is also considered in chapter 6.

3.2 Structural setting

North of 60°N, the East Shetland Basin forms a wide terrace lying immediately basinward of the East Shetland Platform and west of the Viking Graben (Figure 3.1). The basin narrows to the south where it abuts against the Bressay area. The Viking Graben is here at its narrowest point: Jurassic crustal extension occurred across a distance of about 55km at 60°N, compared with approximately 150km at 61°N (Condon, 1988).

The East Shetland Basin is dissected by three main north-south trending, east-dipping Late Jurassic growth faults (Figure 3.1). In the southwest of the basin, this structural pattern defines the Alwyn slope, a transitional terrace between the Bressay area and the deeper
Figure 3.1. Structural context of the Northern North Sea. Dotted lines in inset show the regional seismic grid over the East Shetland Basin.
basins. North of 60°40'N, NE-SW trending faults become more dominant (Figure 3.1), including the major fault separating the Magnus Trough from the East Shetland Basin.

Rift-related subsidence stopped around the end of the Jurassic, although Condon (1988) reported Cretaceous fault movement in the north of the basin. Cretaceous thermal subsidence led to little change in the structural configuration (Morton, 1987); differential subsidence and compaction preserved the Jurassic faults as bathymetric highs in the lower Paleocene. At the beginning of the Paleocene, the East Shetland Platform margin formed a substantial submarine scarp (in the order of 2000'), and water depths were thus effectively constant (i.e. bathyal, >200m water depth) across the East Shetland Basin at this time. No evidence of Paleocene fault activity was observed in this study, although fault activity in the Andrew/Lower Balmoral sequence has been suggested (e.g. Morton, 1982).

3.3 Database

The data used for this chapter comprised 2600kms of 2D regional seismic, with a 10 to 15 kms spacing (Figure 3.1 inset). A total of 158 wells were examined, of which 54 were tied to the seismic data using velocity logs. The few recovered Paleocene cores in the Northern North Sea were examined and are described here. Biostratigraphic data was available for 24 wells in the area.

3.4 Biostratigraphic Framework

A number of stratigraphic frameworks for the Paleocene of the North Sea have recently been published, principally for the Outer Moray Firth and Central North Sea areas. These schemes show some significant differences (Enclosure 3), and vary from 9 sequences (Den Hartog Jager et al., 1993) to 5 (Armentrout et al., 1993) (section 1.4.3). The nomenclature and age dating of the sequences also varies. The introduction of another stratigraphic scheme for this interval is justified in two ways:

a) The detailed study of the North Sea north of 60°N has not been undertaken for over a decade (Morton, 1982; Mudge & Bliss, 1983). The use of the high resolution biostratigraphic framework, combined with recent stratigraphic advances addresses some outstanding stratigraphic problems.
b) The Graphic Correlation Method can define depositional sequences effectively and relatively unambiguously. Its strengths as a correlation tool presents the opportunity to make a comparison of the Northern and published Central North Sea stratigraphies.

The stratigraphy presented here is accompanied by a detailed definition of the sequences, and supported with correlations to previously published work.

**Data & Methodology**

Following the graphic correlation method of Shaw (1964) (section 2.7), a biostratigraphic framework was constructed for the East Shetland Basin and environs. Biostratigraphic data was used from 32 wells, of which 13 were of high quality. Biostratigraphic data quality deteriorated to the north (wells 3/1-1, 3/4-1, 3/11-1, 3/11-2 and 3/17-1) mainly due to poor sampling, which hampered precise correlation into the East Shetland Basin.

The framework was constructed using only the best biostratigraphic data across each interval: where data was ambiguous or unsupported, it was not used. Graphic Correlation terraces are generally elongated as data becomes poorer, so the indicated duration of the sequences is likely to be greater than the true durations. Each depositional episode was established independently in multiple wells indicating the repeatability of the results. However, differences in sampling, faunal preservation, together with the fact that each terrace represents a composite hiatal section (Neal, 1994), inevitably leads to difficulty in accurately defining sequences, as outlined below.

**Results**

Seven depositional units are recognised in the Paleocene of the Northern North Sea: the Maureen, Andrew, Lower Balmoral, Upper Balmoral, Forties, Sele and Balder sequences. As described in section 2.7, the Graphic Correlation method identifies these depositional sequences as periods of common sedimentation in the study area, separated by hiatal intervals (*sensu* Neal *et al.*, 1994), as shown in Enclosure 4. The genesis of these depositional sequences is considered in section 6.2.3.

The biostratigraphic tops and bases of these sequences are outlined in Table 3.1 (see also Enclosure 3). Alternative definitions are described in Table 6.1 (page 219).
Table 3.1. Description of the biostratigraphic events defining the stratigraphic sequences used in this thesis

<table>
<thead>
<tr>
<th>Sequence</th>
<th>CSU value</th>
<th>Simple biostratigraphic definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maureen:</td>
<td></td>
<td>P. americana, O.lens</td>
</tr>
<tr>
<td>Base</td>
<td>506 - 512</td>
<td>E. Trivialis, G. Cf. compressa S.Blow</td>
</tr>
<tr>
<td>Top</td>
<td>554 - 556</td>
<td></td>
</tr>
<tr>
<td>Andrew</td>
<td></td>
<td>P. bulliforme acme</td>
</tr>
<tr>
<td>Base</td>
<td>589</td>
<td>Thalassiphora Cf. delicata</td>
</tr>
<tr>
<td>Top</td>
<td>596</td>
<td></td>
</tr>
<tr>
<td>L. Balmoral</td>
<td></td>
<td>Q. allomorphinoides (Cenodiscus SP.1 RRI acme)</td>
</tr>
<tr>
<td>Base</td>
<td>601 (603)</td>
<td>(P. bulliforme?) P. pyrophorum - S. membranospina</td>
</tr>
<tr>
<td>Top</td>
<td>615 - 619</td>
<td></td>
</tr>
<tr>
<td>U. Balmoral</td>
<td></td>
<td>L. obscurum</td>
</tr>
<tr>
<td>Base</td>
<td>664</td>
<td>A. margarita</td>
</tr>
<tr>
<td>Top</td>
<td>675</td>
<td></td>
</tr>
<tr>
<td>Forties</td>
<td></td>
<td>Rhizammina/Bathysiphon</td>
</tr>
<tr>
<td>Base</td>
<td>678</td>
<td>Aaugustum acme</td>
</tr>
<tr>
<td>Top</td>
<td>687 (approx.)</td>
<td></td>
</tr>
<tr>
<td>Sele</td>
<td></td>
<td>A. augustum, Apectodinium spp. (acme)</td>
</tr>
<tr>
<td>Base</td>
<td>703</td>
<td>C. wardenensis acme</td>
</tr>
<tr>
<td>Top</td>
<td>743</td>
<td></td>
</tr>
<tr>
<td>Balder</td>
<td></td>
<td>D. oebisfeldensis acme</td>
</tr>
<tr>
<td>Base</td>
<td>753</td>
<td>Coscinodiscus sp.1, 2 Bart</td>
</tr>
<tr>
<td>Top</td>
<td>775</td>
<td></td>
</tr>
</tbody>
</table>

Notes:  
(Cenodiscus SP.1 RRI acme) Associated taxa  
(P. bulliforme?) Possible alternative where definition is not constrained

The paucity of taxa in the Maureen sequence hindered precise definition of the sequence, so the continuity of sedimentation in the sequence was uncertain. The Andrew sequence was least well defined: the taxa P. bulliforme acme and Thalassiphora Cf. delicata only occurred in wells 3/22a-1 and 9/4-1. Differentiation of the Andrew and Lower Balmoral sequences is thus tentative. The Lower Balmoral, like the Andrew sequence was a period of predominantly arenaceous deposition. The lower boundary of the sequence was well constrained, in contrast to the upper boundary. The upper boundary is possibly coeval with (FDO) S. membranospina, but an older age (FDO P. pyrophorum, FDO P. bulliforme?) is more likely, given that the paucity of taxa in any section generally results in an artificial lengthening of the range of the depositional episode (Edwards, 1984).
The upper and lower boundaries of the Upper Balmoral sequence were relatively well constrained, as was the base of the Forties sequence. However, the upper boundary of the Forties sequence, and the tops and bases of the Sele and Balder sequences were not well constrained. This was due to the decreasing diversity and abundance of the marine fauna in the North Sea basin as the basin became isolated and anoxic (section 2.7).

Comparison with other frameworks

Enclosure 3 compares the stratigraphic framework of this study with other published stratigraphies (Stewart, 1987; Milton et al., 1990; Mudge & Copestake, 1992a & b; Den Hartog Jager et al., 1993; Morton et al., 1993; Jones & Milton, 1994; Mudge & Bujak, 1994; Neal et al., 1994; Dixon et al., in press; Dixon & Pearce, in press). The schemes are tied through biostratigraphic and magnetostratigraphic correlation to the framework of Neal et al. (1994), the only framework which was accurately tied to a magnetochronostratigraphic timescale (Cande & Kent, 1992, modified 1993 by W. A. Berggren). The magnetochronostratigraphic timescale of Harland et al. (1990) is also shown for comparison.

The framework used here is generally in agreement with the stratigraphies of Den Hartog Jager et al. (1993) and Neal et al. (1994). Differences between the schemes may arise from different study areas; variable sizes and quality of biostratigraphic databases; greater or less integration of well log and seismic data; and different interpretation of sequence stratigraphic models. These differences are considered in chapter 6.

3.5 Stratigraphy

3.5.1 Maureen Sequence

Age: Late Danian

Seismic Data

The top of the Maureen seismic sequence is a surface of basal downlap in the lower Paleocene. The interval is generally too thin to form a mappable seismic package in the East Shetland Basin except where it thickens up at the western margin of the basin (Table 3.2; Enclosures 15 & 16). The seismic character at the base of the Maureen sequence in
Figure 3.2. Graphic Correlation plot of well 3/2b-3. The well shows little evidence of significant Maureen or Andrew deposition.
Figure 3.3. Graphic correlation of well 3/29-2. Note the occurrence of Maureen sequence deposition, and the large Forties sand. The well sits immediately East of the incision mapped in block 3/28 (chapter 5).
Figure 3.4. Graphic Correlation of well 9/8-4. Biostratigraphic data courtesy of Simon Petroleum.
this area is very strong, which is probably due to the preservation of limestones in the sequence. The strong seismic signature diminishes away from the basin margin, coincident with well data indicating the proportion of carbonates decreasing into the basin.

Biostratigraphic Data

Biostratigraphic evidence indicates variable deposition during this sequence. Wells 3/23a-2, 3/23b-3, 3/29-2 and 9/8-4 (Enclosure 5, Figures 3.2 to 3.4) imply sporadic sedimentation during the Maureen sequence, whereas wells 3/19b-3, 3/24-1 and 9/4-1 (Enclosure 6) show little or no evidence of sediment accumulation in this period. Wells 3/22a-2, 3/23b-4 and 9/5b-2 preserve no evidence of sedimentation older than Andrew sequence age (Enclosure 4). Well 3/29-2 has the thickest limestone succession observed in the Maureen sequence, but this is still thin compared to the thickness of the overlying Andrew / Lower Balmoral sequences (Figure 3.3). Thinner Maureen successions were generally more typical (e.g. well 3/23b-3, Figure 3.2).

There are many biostratigraphic markers in the Maureen sequence, but they group into only three or four events which prevents a detailed subdivision by the Graphic Correlation means. The relative age of accumulation in wells 3/23a-2, 3/23b-3, and 3/29-2 is therefore difficult to assess. However the absence of mixing of Andrew and Maureen sequence age fauna indicates that Maureen sequence deposition did occur discretely in the area.

Well Data

The uppermost Cretaceous succession in the East Shetland Basin comprises calcareous argillites. Cuttings record marls (light to mid grey, occasionally red-brown) interbedded with claystones (medium greyish-green to red-brown, moderately indurated, slightly silty, slightly calcareous, glauconitic) and commonly associated with limestone (white to cream, chalky). In wells where the basal Paleocene section is argillaceous, the Cretaceous / Tertiary boundary is clearly defined by a distinct uphole sonic decrease.

The basal Paleocene section commonly comprises reworked chalks and limestones. The carbonate lithologies (chalk, chalky limestone and limestone) are similar to those in the upper Cretaceous. Interbedded lithologies range from sandstones (light to dark grey, fine
As grey laminated mudstone below. Laminations discontinue in last 6'.

Grey homogeneous mudstone containing sub-horizontal, green volcanogenic clasts up to 2cm long.
Fractured, micritic limestone/dolomite with lamination in upper part. No clear bioturbation.

Light grey laminated mudstone. No evidence of bioturbation or current reworking. Lamina picked out by discontinuous brown and white lenses, irregularly spaced, up to 1mm thick.

Pyritized burrows at base?

Clastic white limestone, slightly to very heterogeneous. Irregular thin partings, with clay to silt grade sediment. Occasional larger partings comprise limestone clasts in clay matrix.

Figure 3.5. Graphic log of core 1, well 2/10a-7, recovered from the Maureen sequence. Inset shows position of well with respect to East Shetland Platform and Ninian field.
Figure 3.6. Well 2/10a-7 core photos. (a) An overview of the core from 5129' to 5151'. The top of the limestone at 5144' is shown in (b), demonstrating the existence of deformed clay clasts in the limestone. The limestone also shows variable fracturing, indicating that it was redeposited. (c) Detail from 5150', illustrating the whispy, discontinuous laminations in the siltstone. Note the absence of bioturbation. See text for discussion.
to very coarse, subangular to well rounded) to claystones (dark grey, hard, slightly
carbonaceous, silty).

**Well 2/10a-7, Core 1, 5129' - 5190'.**

Core data from well 2/10a-7 comprises a succession of light grey laminated mudstones,
occasionally interbedded with fractured, micritic limestones clasts, up to 2 ft in thickness
(Figure 3.5). The mudstone laminations (millimetre to sub-millimetre scale) are wispy,
planar to very low angle cross-laminated, with relatively sharp tops and bases (Figure
3.6). No grading is observed. Limestone clasts are slightly argillaceous, laminated,
fractured, and contain deformed clasts (Figure 3.6). The mudstones conform to facies
D2.3 of Pickering *et al.* (1989), and imply deposition from low concentration, low-density
turbidity currents.

The facies observed in core 2/10a-7 indicate that the basal Paleocene was a period of
relative quiescence in the west of the East Shetland Basin, and are interpreted to be of
Maureen sequence age. The occurrence of large limestone clasts indicate that active
degradation occurred contemporaneously updip.

**Conclusions**

Biostratigraphic evidence indicates that limited deposition occurred during the Maureen
sequence in the East Shetland Basin. The sporadic distribution of deposition indicated by
biostratigraphic data, together with the core data from 2/10a-7 and seismic evidence of
distal thinning, suggests that accumulation from low-concentration turbidity currents in the
basin was augmented by mass flow of reworked carbonates from the basin margin. This is
consistent with the unordered mix of such lithologies in wells logs, and biostratigraphic
evidence of reworked Danian and Cretaceous fauna. The occurrence of a good pelagic
foraminiferal assemblage in the succession indicates deposition in a fully marine basin with
an open oceanic connection, probably to the north (Figure 1.3).

Johnson (1987) described Maureen-equivalent formations in the Outer Moray Firth and
Central North Sea. Limited core evidence revealed plastically deformed chalk clasts caught
in or capping a clastic matrix which were interpreted as allochthonous clastic-carbonate
flows. The core in well 2/10a-7 is similar to that described by Johnson (1987), but
a) Line ESBT89 - 208, shotpoints 3700 to 3400

b) Line ESBT89 - 105, shotpoints 700 to 2050

Figures 3.8a & b. Line drawing of ESBT89 lines between the East Shetland Platform and the East Shetland Basin. Compare with Figures 5.5 c to e.
c) Line ESBT89 - 210, shotpoints 400 to 700

- tramline reflector
- No evidence of diverging reflectors

d) Line ESBT89 - 109, shotpoints 4100 to 3800

- tramline reflector
- Toplap

e) Line ESBT89 - 110, shotpoints 600 to 1900

- tramline reflector

Figures 3.8c, d, & e. Line drawings of ESBT89 lines between the East Shetland Platform and the East Shetland Basin. Compare with Figures 3.8a, b. & see for basemap.
Table 3.1
Seismic character of stratigraphic units in the ESB

<table>
<thead>
<tr>
<th>Unit</th>
<th>Stratigraphy</th>
<th>External morphology</th>
<th>Base reflector terminations</th>
<th>Top reflector terminations</th>
<th>Internal architecture</th>
<th>Seismic character</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Maureen Sequence</td>
<td>Wedge; thins rapidly to below seismic resolution</td>
<td>Downlap</td>
<td>Sub-parallel to overlying</td>
<td></td>
<td>High reflector amplitude &amp; continuity where thick</td>
<td>Period of relative quiescence in basin</td>
</tr>
<tr>
<td>2</td>
<td>Andrew &amp; Lower Balmoral Sequences</td>
<td>Marginward-thickening wedge</td>
<td>Onlap to West (against ESP) &amp; downlap to East. Strong base reflector</td>
<td>Toplap to West</td>
<td>Internal downlap &amp; onlap</td>
<td>Reflector amplitude &amp; continuity good but decreases distally</td>
<td>Fan apron onlapping East Shetland Platform</td>
</tr>
<tr>
<td>3</td>
<td>Upper Balmoral Sequence</td>
<td>Marginward-thickening wedge</td>
<td>Basal onlap to West; downlap to East. Discontinuous base reflector</td>
<td>Toplap to West</td>
<td>Reflectors distally subparallel to or downlap base</td>
<td>Fan apron onlapping East Shetland Platform</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Balder Sequence</td>
<td>Sheet, draping underlying</td>
<td>Onlap to West</td>
<td>Onlap to West</td>
<td>None visible</td>
<td>Tramline, but thins laterly</td>
<td>Transgressive unit, significantly volcanogenic</td>
</tr>
</tbody>
</table>
Figure 3.9. Base Paleocene to Upper Balmoral isochron in East Shetland Basin (TWT).
carbonate lithologies are less dominant. Seismic activity was suggested for their transport and deformation in the Outer Moray Firth, although core data was sparse. Seismic reflection data implies that the carbonates in the East Shetland Basin are less extensive than in the Outer Moray Firth, probably due to the absence of intra-basinal highs in the East Shetland Basin.

3.5.3 Andrew & Lower Balmoral Sequences

Age: Selandian to early Thanetian

Seismic Data

The Andrew and Lower Balmoral sequences form thick wedges abutting against the platform margin in the East Shetland Basin and the Viking Graben (Enclosure 10; Table 3.2). Figures 3.8a to e illustrate the changing geometry of the Paleocene strata at the basin margin. The figures highlight the fact that the Andrew to Lower Balmoral depocentres occur where the greatest accommodation existed beside the East Shetland Platform, in blocks 2/5 and 2/10 (Figure 3.9). Subsidiary thickening occurs in blocks 2/15 and 3/17, which may be contiguous. The sequences thin rapidly into the East Shetland Basin and commonly thin over the crests of the Jurassic half-grabens.

In the Beryl Embayment and North Viking Graben, the Maureen / Andrew sequence thins both basinward and marginward; seismic data show the sequence onlapping the East Shetland Platform, and downlapping into the basin (Table 3.2). In block 9/4, the onlap of the sequences is significantly below the level of East Shetland Platform (Enclosure 7). In contrast, onlap of the top reflectors in block 9/8 is approximately level with the platform. The patterns of onlap and isopach variation (Enclosure 8) support other work (Heritier et al., 1979; Mudge & Bliss, 1983) showing a local depocentre in the Beryl Embayment.

Tracing of individual seismic reflectors demonstrates that the lithostratigraphic units identified in the southern East Shetland Basin (e.g. Enclosures 18 & 19) downlap to the north, and are onlapped by the main depocentre around 2/10.
Biostratigraphic data

The available biostratigraphic data suggests that the main clastic influx in the Greater Bressay area began in the Andrew sequence. Biostratigraphic data from wells 3/22a-1 and 9/4-1 indicate deposition initiating approximately coeval with *P. bulliforme* (FDAO) and *Thalassiphora cf. delicata* (FDO). However, the majority of wells indicate significant deposition initiating with the Lower Balmoral sequence. This is notably earlier than the earliest sedimentation in the Bressay area, suggesting that the East Shetland Platform was transgressed in the upper Lower Balmoral sequence (see section 5.6.1).

Log Data: Viking Graben & Beryl Embayment

The Andrew / Lower Balmoral section is up to 2500' thick (9/8-13) south and east of the Bressay area, and decreases in thickness away from the East Shetland Platform (Enclosure 8). This trend is associated with a changing log character as the sands become less 'clean' (e.g. well 9/8-1 versus 9/4a-2A). The thick sands generally have a low gamma profile, interspersed with irregular and laterally variable clay and limestone horizons. Cuttings describe moderately mature sands and sandstones (fine to very coarse; sub-rounded to angular; poorly to moderately well sorted), with occasional glauconite, pyrite, granules and rare pebbles. Some calcareous or siliceous cementation occurs in the sands.

The log character is irregular in the lower part of the unit, indicating thin sand bodies and relatively fine-grained material. Further uphole, upward-increasing and upward-decreasing gamma profiles are observed. These are accompanied by cuttings descriptions of coarsening-upward cycles (well 9/8-1), grading from fine / medium to very coarse grained sands. Neutron-density logs over this interval showed lithologies (sand:shale ratios) remained consistent through the main part of sand bodies, with grain size trends restricted to the upper parts. Log character thus indicates the sequence becoming 'cleaner' and internally more ordered upwards. No cores exist though this interval in the immediate vicinity, but this unit is interpreted to be one of stacked, amalgamated sand bodies.

Log Data: East Shetland Basin

The basal Andrew / Lower Balmoral sand body onlaps against the East Shetland Platform east of Bressay, and thins to the north where it is laterally equivalent to a thick claystone...
Figure 3.10. Well 2/10a-6, cores 1 to 4, Andrew / Lower Balmoral age. Core preservation good except over oil-saturated sections, where hydrocarbons inhibited lithification. The core contains few primary sedimentological structures, and bioturbation is limited. Mass flow deposition is interpreted. See text for details.
succession (Enclosures 11, 16, 17 & 20; see Enclosure 13 for location). Further north, the claystone succession is downlapped by another major sand-prone depocentre in blocks 2/5 and 2/10. Cuttings descriptions from the northern depocentre are similar to those already described. Lithostratigraphic correlations can locally differentiate the sequence into three sub-units which rapidly thin basinward (Enclosures 14, 15, 18 & 19). Correlation of these lithostratigraphic subunits is possible over the south of the East Shetland Basin, but the subunits cannot be correlated north or south into the main depocentres.

Core data: Well 2/10a-6, Cores 1 to 4, 4809' to 4661'.

Cores 1 to 4 show the Lower Balmoral interval in well 2/10a-6. The cores predominantly comprise sands (grey-brown, fine to medium grained, with coarse floating grains and occasional calcite doggers) interbedded with silts (Figure 3.10). A sand:silt ratio of approximately 10:1 was observed over the core. The sand are medium-bedded (3'), commonly massive (not graded), with fining-up tops and occasional erosional bases. Interbedded fines were laminated to slightly cross-laminated, occasionally slightly erosional; dips up to 20° were recorded (Figure 3.11). Contortion of the silt laminasets was observed. Bioturbation was restricted to bed tops in the lower cores, but became more pervasive upwards. Evidence of minor faulting was also observed (post-lithification disaggregation and fluid intrusion).

Conclusions

The cores from well 2/10a-6 show massive beds with planar surfaces, and fining-up tops; the concentration of bioturbation in the fine-grained units; and the contortion of laminated silts immediately overlain by undeformed sands (implying tractional deformation), all consistent with gravity current deposition. The absence of body fossils, the consistent background clay content, the physical and chemical maturity of the sands, and the relative paucity of lignitic material suggest a distal depositional setting. The water depth at the time of deposition of these deposits is unclear in the literature (shallow marine, Morton, 1982 and Mudge & Bliss, 1983; 200m plus, Berggren & Gradstein, 1981; 300 to 500m, Lovell, 1984; over 910m, Parker, 1975; 1km, Bertram & Milton, 1989), but the absence of incision observed on the East Shetland Platform suggests that base-level (wavebase) prevented sediment accumulation (see section 5.6) and baselevel was approximately level with the East Shetland Platform.
Figure 3.11. Selected photos from well 2/10-6 core. (a) & (b) Near top and base of the preserved core (4809' to 4797' & 4673' to 4661'). Visible features include post-lithification fracturing of the core (4809', 4800' & 4799') interpreted as faulting; sharp bed contact (4803.5'); mud rip-up clasts (4670'); calcareous sedimentation (4670-4667'); tines (at 4804', 4664' & 4661') interpreted as flow tops; and dewatering (4661'). (c) (4800'). Detail of core fracturing. Note the large quartz crystal preserved (lower centre). Preservation of large pores separating sandstone suggest that the fracturing was post-lithification. The interpretation is of fracturing followed by opportunistic authigenic quartz growth. (d) (4799'). Detail of bed contact grading over c. 2cm from homogeneous medium / coarse sand to silt. Interpreted as sharply decelerating density current deposition. Ruler for scale.
The sands in the 2/10a-6 core conform to the B1.1 classification of Pickering et al. (1989), implying rapid mass deposition from high concentration turbidity currents, although dewatering structures are notably absent. The finer sediments can mostly be classified D2.1 (Pickering et al.), indicating deposition from low concentration turbidity currents. This supports wireline log data indicating that the unit predominantly comprises sands and silts, probably in numerous stacked flows. Log character indicates the sequence becoming internally more ordered upwards which is consistent with upward retrogradation of the sequence leading to the subsequent transgression of the East Shetland Platform.

This information, combined with the seismic observations of a marginward thickening wedge, suggest that the Andrew / Lower Balmoral sequences formed fan aprons in the East Shetland Basin and Beryl Embayment. The minor faulting in core 2/10a-6 could indicate proximal oversteepening led to slumping which in turn fed sediment into the basin. No evidence for active faulting along the platform margin was observed, either divergence of seismic reflectors or direct imaging of a fault (Figure 3.8). The correlation between the thickness of the Andrew / Lower Balmoral sediments at the basin margin and accommodation space as observed on seismic is interpreted as sediment ponding. This concurs with the study of Condon (1988).

Seismic mapping demonstrates that sediments of the block 2/10 depocentre downlap the claystone facies which are laterally equivalent to the Beryl Embayment depocentre. The East Shetland Basin depocentre is thus younger. Seismic data demonstrates that the thick, proximal claystone facies also thin distally: they thus represent part of the 'proximal' Andrew / Lower Balmoral deposition. Biostratigraphic data cannot constrain the timing of the depocentre shift to the East Shetland Basin, nor the relative age of the onlap of the East Shetland Platform.

This study does however differentiate the Maureen and Andrew / Lower Balmoral sequences in the Northern North Sea. This clarifies the different interpretations of the sequences in the literature (Heritier et al., 1979; Morton, 1982; Mudge & Bliss, 1983; Knox & Holloway, 1992; Mudge & Copestake, 1992b; Morton et al., 1993). In addition, this study considers that there was no active faulting along the East Shetland Platform during the Andrew / Lower Balmoral sequences.
3.5.4 Upper Balmoral Sequence
Age: Early Thanetian

Seismic Data

Seismic data indicates that the Upper Balmoral sequence has a similar gross form to the underlying Andrew / Lower Balmoral wedge, but that it thins less rapidly into the basin (Enclosure 10; Table 3.2). Figure 3.8 shows that downlap of the sequence onto the basin margin, and possible coastal onlap at the margin edge (Figure 3.8a). Figure 3.8a also shows toplap of the base Upper Balmoral sequence. This seismic evidence indicates that transgression of the East Shetland Platform occurred along the margin of the East Shetland Basin during the upper Lower Balmoral sequence, or the lower Upper Balmoral sequence.

Log Data

The Upper Balmoral sequence comprises grey to grey-brown claystones (firm, non-calcareous, micaceous) interbedded with banded calcareous siltstones, loose sands and occasional sandstones. Cuttings descriptions and wireline log characters vary little across the basin. Gamma and sonic profiles commonly increase upwards (e.g. Enclosures 14 & 16). The sequence thins distally but less abruptly than the underlying Andrew sequence.

Arenaceous deposition principally occurred in the basin (Figure 3.12; Enclosures 11 & 12). Biostratigraphic differentiation of these sands was difficult where they were overlain by Forties sands, but they could be separated on seismic data. The distribution of these sands was elongate on a north-south trend. Comparison with the Forties facies map (Figure 3.13) highlights the absence of updip more proximal facies.

Well 211/29-1, Core 1

Core 1 in well 211/29-1 allows some limited observations to be made on the Upper Balmoral sequence. Preservation of the core is appalling, but the continuity of the facies allows some generalisations to be drawn.

Core fragments comprise pale grey to yellow-brown very fine siltstones, laminated on a sub-mm to cm scale. Occasional fine silt to coarse, sub-rounded to sub-angular sand clasts
Figure 3.12. Schematic facies map of the Upper Balmoral Sequence in the Greater Bressay area.
Figure 3.13. Schematic facies map of the Forties Sequence in the Greater Bressay area.
occur. The sands and silts are relatively well sorted where not bioturbated, with chemically mature compositions: mainly quartz and muscovite, and variable clay content (1 to 20%). Pervasive bioturbation and poor preservation prevent the identification of laminasets or bedding planes. Clay rip-up clasts occur, up to 2cm in length, generally with elongate aspect ratios at angles up to 50° from bedding. Elongate lignite fragments are common.

Laminae are planar-, ripple- or cross-laminated, and predominantly become bioturbated upwards, implying relatively rapid deposition, and / or the intermittent introduction of bioturbating fauna. Folding and contortion of the lamina over a 10cm interval occurs interbedded between horizontal parallel-laminated beds (6028.5'; Figure 3.14). This may be due to slumping or dewatering, or traction dewatering caused by a succeeding flow.

The sediments lack tool or scour marks, but otherwise closely conform to the C2.3 classification of Pickering et al. (1989), typically exhibiting T_{bed} (or T_{bc}) internal structures of Bouma (1962). The depositional processes depositing these sediments was probably grain-by-grain deposition from suspension, followed by tractional transport from bedload (Pickering et al., 1989). Sediments such as these could have been deposited by turbidity currents or contour currents. In this case, the presumed absence of strong currents in the basin suggests that relatively dilute turbidity currents were responsible for their deposition.

Conclusions

The Upper Balmoral sequence regression deposited primarily argillaceous sediments across the basin with the exception of the southeast East Shetland Basin and Viking Graben. The Viking Graben sediments are equivalent to the Heimdal Member of Mudge & Copestake (1992b). Biostratigraphic data indicates a significant break with the subjacent strata, and the sequence is not therefore merely a transgression associated with the underlying Lower Balmoral sequence. The sequence approximately correlates with the MT5 interval of Morton et al. (1993), who described a shift in the provenance of units MT4 and MT5 from the central / south to the north of the East Shetland Platform.

The arenaceous facies in the basin are assumed to be deep marine gravity flow deposits. Tentative correlation of the unit around block 3/24 (Enclosures 11 & 12) suggests that this area may have acted as a conduit for sands to the southeast (Figure 3.12). Seismic data
Figure 3.14. Selected photos from Core 211/29-1. Core preservation amounted only to small samples preserved in plastic bags, so no log was constructed.

(a) (6028.25). Dewatering structure in silt dominated bed. Note contorted laminae overlain by planar, parallel laminae, and overlying steeply dipping laminae presumably deformed during same movement. Length of sample c. 6" (12cm). (b) (depth unknown). Detail demonstrating upward change from planar- to ripple-lamination, followed by bioturbation completely reworking sediment. Interpreted as decelerating density current deposition followed by intra-flow recurrence of bioturbation. Ruler for scale (dark/light rectangles = cms). Arrow = way-up. (c) (depths unknown). Similar to (b) illustrating bioturbated homogenization of sediment between flows. Ruler for scale (dark/light rectangles = cms). Arrow = way-up.
demonstrate downlap and possible clinoforms in the Upper Balmoral sequence on the basin margin, indicating that progradation took place in this area. The evidence of toplap in Figure 3.8d is unique and inconclusive, but together with the ponding of the underlying sequences against the basin margin suggests that sediment was fed into a narrowed basin which possibly experienced minor margin uplift.

3.5.5 Forties Sequence
Age: mid-Thanetian

North of the area of good biostratigraphic control in blocks 3/22 to 3/24, the Forties sequence could not be differentiated from the Sele sequence on log or seismic data. This section is therefore limited to the areas where discrete Forties deposition was identified.

Seismic Data

The Forties sequence was only differentiated on seismic in the Greater Bressay area. Its characteristics are described in chapter 5 and Enclosures 26 and 27.

Log Data

The Forties sequence on the Alwyn Slope is an upward-coarsening succession in the order of 250' thick, which downlaps towards the platform margin. To the north, the sequence thickens in well 3/17-1 but then thins and is not interpreted in block 3/11 (Enclosure 17). Enclosures 11 & 12 show the Forties sequence thinning eastward on the Alwyn slope but expanding again in the southern East Shetland Basin and Viking Graben. This thickening is predominantly due to the incoming of a local sand body, which is most dramatic in well 3/29-2 (350' 'boxcar' sand, i.e. a clean sand with low gamma values, bounded above and below by shales / silts). The distribution of the sand body is not well constrained, but it does not continue northwards - it is not observed in 3/23b-4, and appears to thin through 3/24b-2 into 3/24-1 (Figure 3.13). The distribution of the sands east and south of Bressay correlates well with the shallower gradient of the graben floor in the area (Figure 5.2).

In block 9/8 the Forties interval thickens away from the platform. The sequence in well 9/8-4 is comparable to that in 3/28b-3 (200' thick, and coarsening up from silts to sand), but wells 9/8-1 and 9/8-5 display a thicker (450') more heterolithic log character with no
observable fining- or coarsening-up trends. The thickening of the Forties / Sele sequence is observed on seismic data to be separated from the platform by an area of slope-proximal thinning (Enclosure 9), which is likely to represent slope-bypass occurring across the steep graben margin. The basinal extent of this unit was not constrained by the dataset.

**Conclusions**

The distribution of the Forties sequence in the East Shetland Basin is not well constrained. The Forties / Sele interval isopach around the 9/8 area indicates that slope bypass took place; Dixon & Pearce (*in press*) indicated that no significant sand deposition further into the basin. In block 3/29 the Forties sequence comprises a clean sand but it is of limited areal extent. The position and extent of this sand infers an updip point source. As argued in section 5.7.1, the entry point of sediment into the Viking Graben probably occurred through a nick-point in the East Shetland Platform in block 3/28.

This contrasts with the situation on the Alwyn Slope, where limited Forties sequence deposition occurred. Further north, there is no clear evidence of Forties sedimentation at all. Thus the character and distribution of the basinal sands was controlled by the bathymetry of the platform in the Bressay area.

The Sele Formation contains a microfauna comprising diverse (mainly *Coscinodiscus*) diatom assemblages, and significant amounts of land-derived palynomorphs (Stewart, 1987; Mudge & Copestake 1992b). The paucity of benthonic microfauna, combined with the preserved lamination of the sediments indicates anoxicity. Mudge & Copestake (1992b) considered that the Forties Formation in the Outer Moray Firth is represented in the Northern North Sea by a condensed section; Dixon and Pearce (*in press*) also described an absence of basinal sands. This study indicates that some basin-margin Forties sequence sands do exist in the basin, but the basinal extent of these sands is not clear.

**3.5.6 Sele Sequence**

**Age:** Mid- to late Thanetian

As noted in the previous section, differentiation of the Sele and Forties sequences was not possible away from the areas of good biostratigraphic control. This section considers the deltaic deposits of Forties / Sele age in the East Shetland Basin, the Ninian delta.
**Seismic Data**

Immediately north of the Bressay High, the Forties / Sele sequence extends in a northerly trend, thinning into block 3/17 before thickening up into the main body of the delta in the central East Shetland Basin (Figure 3.15). Comparison of the Forties / Sele isochore with the base Paleocene structure map shows that the sequence thickens approximately along strike (Figure 3.16). The main depocentre in the Ninian delta is offset to the east from the underlying sub-Upper Balmoral sequences (Figure 3.9): the embayment of the main depocentre in UKCS blocks 3/3, 3/8 and 3/9 mirrors a promontory in the underlying sub-Upper Balmoral sequences. The position of the main Ninian depocentre is observed to lie between two Jurassic fault lineaments. The Ninian delta thins to the north, and laps out distally against the regional paleoslope of the basin. There is no evidence of erosional toplap at the feather-edge of the delta.

The uppermost part of the Ninian delta is commonly identified by a strong 'tramline' reflector, which corresponds to a coarsening-up sequence in well logs (the 'topset' sands of the Ninian delta; chapter 4). Can the extent of the topset sands be approximated by the extent of the tramline interval on regional seismic data? Updip, the sub-horizontal seismic topsets onlap the underlying Upper Balmoral sequence (Enclosure 10; Figure 3.17a), but the characteristic 'tramline' reflection continues until the basin margin (Figure 3.8a). Correlation of the base of the interval is difficult because a transparent zone immediately beneath the Balder 'tramline' obscures the seismic pick as the Sele thins marginward. Distally, the seismic tramline is observed to discontinue before the offlap break (Enclosure 10; Figure 3.17b & c).

Some geometries tentatively identified as delta lobes (as described in chapter 3) are observed on regional seismic (Figure 3.17), and occasional subsidiary lobes are observed on the delta margins (Figure 3.18).

**Log Data: Greater Bressay Area**

The Sele sequence in the southern East Shetland Basin (block 3/23) is described on well logs as comprising light to dark grey banded claystones (soft, streaky, with occasional pyrite nodules), locally grading to banded siltstones. In the Beryl Embayment where the unit becomes thicker, a coarsening-up sequence of sands (light brown to brown, clear,
Figure 3.15. Base Forties to Top Balder (Ninian delta) isopach (TWT) in the East Shetland Basin.
Figure 3.16. Base Paleocene time-depth map in the East Shetland Basin (TWT). Note the change in scale. Compare with the Ninian delta isochron.
Figure 3.17. Line drawings from regional seismic lines. (a) Proximal onlap of the Ninian delta onto the underlying Upper Balmoral sequence. (b) A portion of the distal delta, just east of the Ninian field 3D survey (chapter 4). Note the discontinuation of the 'tramline' reflector towards the offlap break of the delta (see Enclosure 10 for entire line). (c) Discontinuation of the 'tramline' reflector, and the offlap break of the delta. Internal seismic reflectors are weak at the right hand side.
Discrete lobe fed by (coeval with) sands preserved in upward-coarsening 'topset' sands in Ninian area.

Figure 3.18. Seismic line ESBT 105. Alternative interpretations of the distal lobes of the Ninian delta. (a) Tracing of original seismic line. (b) Interpretation of topsets as coeval with distal lobes. (c) 'Topsets' are relatively late (post delta) features confined to the top of delta area, possibly trapped by accommodation space created above the delta by compaction of the delta sediments. Insets show diagrammatic relationship of bodies: wavy line = unconformity.
frosted to milky, fine to coarse grained, occasionally poorly cemented, lignitic) and silts is observed.

In the block 9/8 area, where the Forties and Sele sequences can be differentiated, a marked thickening of the Sele sequence occurs across the platform edge. The base of the sequence is well defined at the top of the underlying Forties shale, which separates the two (Forties / Sele) cleaning-up intervals. Further north in block 9/4, the sequence becomes markedly thinner, and shale-prone. Limited well and seismic data to the east indicates that the intervals thickens again in a basinward direction (e.g. 3/30a-1; Figure 3.19).

Log Data: East Shetland Basin

Enclosures 15 & 20 show the variation of the Ninian delta in the main depocentre. The upper boundary of the topsets as defined in the Ninian 3D seismic dataset is marked by a very sharp break in the sonic log in blocks 3/3 and 3/2; this is also observed in well 3/1-1 (Enclosure 21). The base of the topset sands (see section 4.10) is observed not to correlate with a consistent lithostratigraphic pick, and is not interpreted on well logs. The lateral continuity of reflectors in the delta stratigraphy is shown to be very limited in chapter 4, and clinoforms are not considered to correlate between wells on the regional correlations.

Within block 3/11, relatively close well spacing allows the sequence to be observed thinning towards the platform margin (Figure 3.20). Wells 3/11-1 and 3/11-2 in the east of the block record a clear upward-diverging gamma/sonic trend representing interbedded sands (loose, white to clear, fine, subangular to subrounded quartz grains) and silts (light to medium grey, slightly calcareous, micaceous), which culminate in cleaner sands (clear to milky, medium to coarse grained, subrounded, well sorted). The upward transition into the Balder sequence is rapid but continuous. Further west, wells 3/11-3 and 3/11-6 show a much thinner Forties / Sele sequence (<120' as opposed to >250'). Enclosures 18 & 19 demonstrate that the sequence thickens into block 3/12 before thinning again distally. (Note that well 3/14-1 (Enclosures 19 & 20) has a sharp basal sand, which is a common characteristic of the Sele / Forties sequence further north.) Wells further towards the basin margin generally show a sequence of unbroken shales at the top of the Paleocene interval: no evidence of a significant erosion surface was observed in any wells close to the East Shetland Platform (e.g. in blocks 2/5, 2/10; Enclosures 16).
Figure 3.19. Schematic facies map of the Sele Sequence in the Greater Bressay area.
Figure 3.20. Well correlation in block 3/11 highlighting the lateral thinning of the Ninian delta towards the basin margin.
Enclosures 20 accentuates the regional paleoslope of the East Shetland Basin (Figure 3.16), and implies that across the lapout of the Sele / Forties sequence (blocks 211/21 to 211/24), northward progradation was limited by sediment supply and / or the paleoslope of the bathymetric profile. This infers that in the northern East Shetland Basin, deposition of the delta occurred along strike, from the south.

**Conclusions**

The lapout of the Ninian delta to the northwest infers that the development of a delta / coastal complex did not occur along the entire length of the basin margin during relative sea-level fall. This supports the view that sediment input was predominantly from the southwest of the basin (Rochow, 1981; Morton, 1982; Mudge & Bliss, 1983). It is also indirectly supported by the fact that the drainage area for the basin - the East Shetland Platform - narrows northward (Figure 3.1): sediment transported into the basin would thus have originated largely from the southwest. This is consistent with the isochron data showing thickening parallel to strike i.e. that accommodation was a control.

Evidence of significant erosion and incision is observed in the Bressay area (chapter 5), but no erosion is observed in the East Shetland Basin on well log or seismic data. It was hypothesised that there might be a change in well log character at the base of the unit towards the edge of the delta, but no consistent trend in the character of the basal sand could be identified. From the northward lapout of the delta, and the absence of erosional toplap, regression of the delta is inferred to be 'normal' as opposed to 'forced' as demonstrated for the proximal Bressay area in chapter 4 (Posamentier et al., 1993). Obviously this observation is limited by the resolution of the data, but equally it would be expected that 'normal' regression would ultimately be observed downdip of an area showing evidence of 'forced' regression.

Seismic evidence clearly indicates topsets onlapping the subjacent Upper Balmoral stratigraphy (although post-Balder subsidence has moved the point of apparent onlap further basinward) which implies that base level fell below the level of the East Shetland Platform. The lack of evidence for erosion in wells close to the East Shetland Platform margin is of note because even an erosive shale-on-shale contact might be expected to be observed on wells logs, given that the Sele claystones are unusually quartz & montmorillonite- / smectite-rich (D. Ware, *pers. comm.*). The absence of correlatable log
breaks may therefore suggest that the base of the Forties / Sele sequence is not erosional along the margin. This is consistent with the progradation direction of the delta, and the seismic isochron data, which indicates that sediment supply may have partly been supplied by longshore drift. This concurs with the interpretation of Mudge & Bliss (1983).

The basinward offset of the Sele / Forties and underlying sub-Upper Balmoral depocentres (compare Figures 3.15 and 3.9) may indicate that the intervals had similar sediment entry points on the basin margin. However, it is likely that the continuing subsidence of the basin (differential subsidence due to both compaction and thermal subsidence) was a significant control on the position of the delta depocentre. The observed thickening of the Ninian delta over the Jurassic faults in the Ninian 3D seismic data is comparable to the situation observed in the Outer Moray Firth (own unpublished work). This is consistent with the interpretation of ponding of the Paleocene sediments as differential compaction and thermal subsidence continued. In both the Outer Moray Firth and East Shetland Basin cases, although at first significant, high sediment supply soon infilled the pre-existing basin floor bathymetry.

The sequence to the south of 60°N is thickest in the Beryl Embayment, and regional mapping has shown this to be part of a coastal system stretching over the southern East Shetland Platform and Fladen Ground Spur (e.g. Morton, 1982; Mudge & Bliss, 1983; Galloway et al., 1993). The detailed distribution of the Sele interval in the Beryl Embayment is dealt with by Dixon & Pearce (in press).

The distribution of the tramline seismic reflector as an indicator of the Ninian topset sands is believed to be valid from the close correlation of the seismic reflectors and well log stratigraphy in the Ninian 3D dataset (chapter 4). Although the tramline reflector continues updip, it is strongest across the main body of the delta (Enclosure 10). The topsets sands are interpreted as not extending to the edge of the delta (Figures 3.17 & 3.18).

The Ninian delta is considered in greater detail in the succeeding chapters. The relationship between the distal lobes and the topsets is discussed in section 4.10. Sections 4.12 and 6.3 review possible analogues for the delta.
3.5.7 **Balder Sequence**  
**Age:** late Thanetian to early Ypresian

**Observations**

The character of the Balder sequence in proximal wells varies with that observed in basinal wells in the deeper basins. In the East Shetland Basin, the Balder sequence comprises varicoloured silty, tuffaceous claystones grading to siltstones. The base and top of the sequence are defined on the upper and lower strong gamma-sonic bows, in common with other authors (e.g. Mudge & Copestake, 1992b; Timbrell, 1993; Dixon *et al.*, *in press*).

Although silty in some wells, the interval is noticeably more silty or sandy in wells 2/10-4, 2/10-5 and 2/10-8, and lignite is recorded in the cuttings descriptions of well 2/5-11. In addition, the 'tramline' reflector which is characteristic of the Balder in the basin shows a more progradational character in blocks 2/5 and 2/10 area.

**Conclusions**

All previous work has concluded that the Balder sequence is a time of relative transgression, and this interpretation is again supported here. As in the Holocene shelves of today, rapid relative sea-level rise during the Balder sequence probably locked sediment to the coast (Johnson & Baldwin, 1986). No Balder-equivalent sands are observed in the East Shetland Basin, unlike in the Beryl Embayment (e.g. Forth & Gryphon fields).

Regionally, the Balder tuff thickens to the north (Knox & Morton, 1988; Figure 1.11), and it is believed to have been sourced by the proto-Icelandic plume that generated the early basalts of East Greenland and the Faeroes (Morton & Knox, 1990).

**3.6 Summary & Conclusions**

a) A new, high-resolution biostratigraphic framework is presented for the Paleocene of the Northern North Sea. It demonstrates that there are at least six and probably seven depositional sequences in the area, which broadly concur with the main depositional units recognised for other areas of the North Sea.
b) The stratigraphic framework improves on the resolution previously available in the Northern North Sea. The framework differentiates the Maureen and Andrew / Lower Balmoral sequences, and resolves some of the ambiguities of previous work in the area.

c) There is no evidence of Ekofisk Formation age deposition in the Northern North Sea, and only sporadic evidence of Maureen sequence age sediment accumulation. The contrast with the significant carbonate 'megaturbidites' recorded in the Outer Moray Firth (Johnson, 1987) is attributed to the absence of intra-basinal highs in the East Shetland Basin.

d) There is no evidence for active faulting during deposition of the Andrew / Lower Balmoral sequences in the study area. This conclusion disagrees with most previous authors, but concurs with the work of Bertram & Milton (1989) and Condon (1988). The sedimentation was instead simply ponded against the basin margin, and filled up the available accommodation space.

e) The main depocentre in the East Shetland Basin is younger than the comparable depocentre in the Viking Graben. The two areas are separated by thick successions of laterally-equivalent claystones which thin rapidly away from the basin margin.

d) No evidence was observed of incision on the top of the delta in the East Shetland Basin, nor of significant erosion at the updip margin of the delta. The data supports the interpretation of previous authors that the delta largely prograded from the southwest.

e) Seismic correlation indicates that the delta topsets onlap the underlying Upper Balmoral sequence to the west, and discontinue before the edge of the delta to the east.
Chapter 4
The Ninian Area

4.1 Context

This chapter describes the Paleocene stratigraphy in the block 3/3 area. It focuses on the description and the evolution of the Ninian delta which has not been described since Parker (1975). This detailed study compliments the regional work described in chapter 3. The only other published 3D seismic study of the Paleocene in the northern North Sea is that of Milton & Dyce (in press).

4.2 Introduction

The Ninian field is situated in UKCS blocks 3/3 and 3/8 in the East Shetland Basin, 40 km east of the East Shetland Platform (Figure 4.1a). Two 3D seismic surveys were obtained over the field, the main structure of which is a westerly-dipping Jurassic fault block. This chapter describes the results of a detailed mapping of the Paleocene interval undertaken using the 3D seismic data and well log data from 23 wells. The high density of data available over the Ninian field allowed a depositional model to be developed for the basin, which was extrapolated and tested regionally.

This chapter describes the stratigraphy in the Ninian area, mainly dwelling on the Ninian delta, which is defined here. This is followed by discussions of the depositional processes in the Ninian delta (section 4.9), the genesis of the 'topset' sands (section 4.10), the nature
Figure 4.1a. Context of the East Shetland Basin and the Ninian Field in the Northern North Sea.
of the abandonment of the delta (section 4.11), and a consideration of delta analogues (section 4.12). Chapter 6 integrates the observations from chapters 4 and 5, and considers the study in the broader perspective. The following terms are defined here to clarify the text: the Ninian field, covered by the Ninian 3D seismic data, lies in blocks 3/3 and 3/8; the Ninian area comprises the blocks 3/3 and 3/8 and those immediately juxtaposed (blocks 3/2, 3/4, 3/7, 3/9, 3/13 and 211/28). The Ninian delta is the clinoform / topset package of Forties / Sele sequence age clearly observed on seismic data in the basin.

4.3 Database

The data used for this chapter comprised two 3D seismic surveys over the Ninian field covering a total of 212 km². The survey inline (dipline) spacing was 25 m, and the surveys were oriented at 36 degrees following the direction of the Jurassic faults (Figure 4.1b). Twenty-three wells obtained wireline log data over the Paleocene interval. No Paleocene core was cut in the Ninian field although a short core (49') was cut in well 3/3-11, which lies 4 km northeast of the area of the seismic data. No Paleocene biostratigraphic data was available within the field. This high density dataset was extrapolated to the rest of the East Shetland Basin study area using 2D, well log and core data (chapter 3).

Synthetic 3D seismic data can generate seismic lines at any angle through the survey ('random lines') and this facility was used to directly correlate wells in the survey. In addition, seismic planes were generated through data (Figure 4.2) at selected time-depths ('time slices') and parallel to the Balder horizon ('horizon slices').

4.4 Stratigraphy

The stratigraphy in this chapter is constrained by a biostratigraphic framework constructed for the northern North Sea using the Graphic Correlation method (sections 2.7 and 3.4). The depositional sequences defined in the East Shetland Basin (Enclosure 3) are the Maureen, Andrew / Lower Balmoral, Upper Balmoral, Forties / Sele and Balder sequences. This stratigraphy is compared with other published stratigraphies in chapter 6.

Due to the lack of good biostratigraphic control over much of the East Shetland Basin, the Andrew / Lower Balmoral and Forties / Sele sequences could not be differentiated in the Ninian area. The sequences in the Ninian area were correlated to the regional framework
Figure 4.1b. Basemap of the Ninian 3D surveys showing orientation of surveys, position of selected lines and well data.
Figure 4.2. Orientation of time & horizon slices in seismic data. Time slices are generated at a constant time-depth; horizon slices are generated with a constant (+ve or -ve) shift from a chosen geological horizon. Note that the horizon slice 100ms below the geological horizon A cuts geological horizon B which dips at a steeper angle. This is similar to the situation in Ninian in which a horizon slice 140ms below the Balder pick (i.e. A in this case) cuts the Sele clinoforms (B).
using limited biostratigraphic data (wells 3/7a-7, 3/4-1 & 211/28-5) and regional seismic
correlation from the areas of good biostratigraphic control (the south East Shetland Basin /
Viking Graben area; see chapter 3). The Forties / Sele sequences comprise the Ninian delta
over much of the East Shetland Basin.

4.5 Maureen Sequence
Age Late Danian

Seismic Data
The Maureen sequence generates a thin, laterally discontinuous seismic reflection which is
downlapped by the overlying Andrew / Lower Balmoral sequences (Enclosures 22, 24).

Well Data
The Maureen sequence is up to 120' thick in the Ninian area. The boundary with the
underlying Maastrichtian marls is marked by a sharp to gradational uphole decrease in
sonic and resistivity profiles and commonly an increase in gamma values (Enclosure 23).
The top of the unit is defined by a sharp fall in the sonic and resistivity logs, but no
distinctive gamma log character; this boundary is abrupt in Ninian field area.

Cuttings describe both the Maastrichtian and Maureen sequence intervals as comprising
slightly to very calcareous claystone, commonly silty and of variable colour (grey-green,
light grey, brownish grey). Both intervals contain glauconite, pyrite and reduction spots.

Conclusions
Evidence of reducing marine conditions is provided by the occurrence of glauconite,
pyrite, and reduction spots. The sonic and resistivity logs in the Ninian area clearly
distinguish the unit from the overlying and underlying stratigraphy.

The sharp sonic log breaks imply that this unit has a lithological composition or / and
compaction history distinct from that above or below. The unit is interpreted to have a
discrete composition or / and be bounded by sedimentary discontinuities (hiatii or
unconformities). Sparse biostratigraphic data from the Ninian area indicate the occurrence
of Maureen sequence taxa \( (G. \text{Beccariiformis}, G. \text{psuedobulloides}, \text{& } S. \text{trilocunoides}) \) and the sequence is interpreted as accumulating slowly. This is consistent with the description of the Maureen sequence in chapter 3. The unit is equivalent to the Maureen Formation of Mudge & Copestake (1992b).

### 4.6 Andrew / Lower Balmoral Sequences

**Age:** Selandian to early Thanetian

#### Seismic Data

This unit comprises relatively discontinuous low amplitude reflectors. It exhibits vertical and lateral reflector variation, with evidence of downlap, bidirectional downlap, and onlap, both internally and onto its lower boundary (Enclosures 22, 24). Neither the lower or upper boundaries are themselves strong reflectors but each is defined by seismic reflector terminations. Isochrons of the sub-Forties / Sele time-thickness demonstrate thinning perpendicular to strike around the inflexion of slope (Figure 4.3). This coincides with a change in reflector geometry across the Jurassic fault crest, with the Andrew / Lower Balmoral and probably also Upper Balmoral reflectors onlapping the paleoslope to the west (Enclosure 24). Onlap occurs only to the west against the break in slope. West of the break of slope, basal seismic reflectors in the Andrew / Lower Balmoral sequences downlap predominantly to the east with low angle to subparallel dips.

#### Well Data

This interval comprises quartz sandstones interbedded with non-calcareous mudstones and occasional limestones, contrasting strongly with the underlying mudstones. In the Ninian area this unit is up to approximately 500' thick. The gamma responses of the sandstone and claystone intervals are of irregular (not "boxcar") character. The upper boundary of this unit is picked on the change to a consistent resistivity profile, lower sonic values and a silty-claystone cuttings description (Enclosure 23).

Cuttings describe poorly cemented sands, relatively immature (subrounded to angular; rarely rounded) with moderate to very poor sorting (very fine to very coarse, rare gravel). A grey to white clay matrix is common with traces of glauconite and pyrite, occasional orange-brown quartz staining and local quartz or calcite cement. Interbedded mudstones
are non- to slightly calcareous, slightly silty, with traces of carbonaceous and pyritic material, grey / green to brown in colour and variable fissility. Lignite occurs occasionally. The sand to shale ratio in the Ninian area (calculated from gamma log data using the mean gamma maxima / minima as a cut-off) showed no regional trend. It is likely that variation in the gamma logs scales obscured any trend, particularly as gamma logs were commonly not normalised in older wells (pers. comm.. D. Ware).

**Observations**

On individual gamma logs the gamma 'baseline' of the Andrew / Lower Balmoral sands is notably higher than for the Sele sequence sands (Enclosure 23). This may be due to different mica contents, although this was not indicated in cuttings descriptions. The high gamma 'baseline' therefore probably indicates that the Andrew / Lower Balmoral sands are chemically immature. This is consistent with the physical immaturity described in sand cuttings. In addition, glauconite and pyrite indicate a history of reducing marine conditions. The occurrence of carbonaceous material need not necessarily indicate nearshore environments, as it is commonly carried offshore. It is inferred that these Andrew / Lower Balmoral sands did not undergo significant reworking during transport, implying a relatively narrow and / or low energy shelf updip.

**Conclusions**

The sharp change in sediment calibre between the Maureen and Andrew / Lower Balmoral sequences in the Ninian area implies that this reflects a change from hemipelagic to margin-derived detrital sedimentation. This is supported by the thickening of the unit towards the basin margins seen on regional seismic lines, the change in seismic reflector character across the break in slope in the 3D survey, the contrast in depositional style with the subjacent Cretaceous and Danian strata on seismic data and the relatively short transport history inferred from the physical and chemical immaturity of the sands. This concurs with previous work which interpreted the Andrew / Lower Balmoral as being associated with significant contemporaneous hinterland rejuvenation (e.g. Parker, 1975, Knox *et al.*, 1981; Morton, 1982; Mudge & Bliss, 1983; Jones & Milton, 1994; Enclosure 2).

Laterally equivalent core (well 2/10a-6, 30 kms to the west of the Ninian Field; section 3.5.3) shows the deposition style of the unit to be dominated by mass flow (turbiditic)
processes in a more proximal position. The lateral change in 3D seismic continuity, the immature log descriptions, and the 'ratty' well log characters in the Ninian area are consistent with deposition by gravity flow processes, although no core confirmation of this was possible around Ninian.

The slope break imaged directly east of the Jurassic footwall high in the 3D surveys occurs where compaction and thermal subsidence combine to form the greatest local subsidence (Figure 4.3). The change in reflector geometries and time-thickness across the break of slope probably indicate displacement of sediment in response to slope failure (oversteepening) or slope bypass (for angles of greater than ≈1°, density currents will not deposit; E. Mutti, pers. comm.). The observed downlap and bi-directional downlap imply that deposition occurred in discrete, isolated depocentres, indirectly supporting the interpretation of mass flow deposition.

No direct evidence of base-level was observed in the sequence in the East Shetland Basin. The basin was however marine and probably reducing at the time of deposition, as indicated by glauconite, pyrite, and biostratigraphic data.

4.7 Upper Balmoral Sequence

Age: Early Thanetian

Seismic Data

This unit can be subdivided on seismic character into a discontinuous, low amplitude lower section and an upper relatively transparent section. It exhibits modest lateral reflector variation with evidence of downlap, bidirectional downlap, and possibly onlap both onto its lower boundary and internally (Enclosures 22, 24). Reflectors are generally discontinuous, and predominantly downlap to the east at a relatively high angle to the basal seismic surface. The lower and upper boundaries of the sequence are weak reflectors, but are identified by changes in reflector downlap patterns. As noted previously, the isochron of the sub-Sele time-thickness show a thinning trend parallel to strike around the inflexion of slope. An isochron of the Upper Balmoral sequence itself reveals little, for variations in the seismic pick obscure the detail of the isochron. Any changes in reflector terminations at the base of the sequence are subtle: Upper Balmoral reflectors possibly onlap to the west as in the Andrew / Lower Balmoral interval, but less clearly.
Figure 4.3. Base Paleocene to Upper Balmoral isochron. The contours and shape of the surface represents the base Paleocene surface in time. The colouring on the surface represents the thickness of the overlying base Paleocene to top Upper Balmoral isochron. The diagram illustrates the thinning of the isochron across the break of slope. Together with the observation of onlap against the break of slope on vertical seismic (Enclosure 24), this implies that slope bypass occurred. The data at the south of the dataset do not fit this interpretation, where there is a change in the strike of the underlying Jurassic fault trend.
Log Data

This unit is characterised on logs by relatively consistent gamma and resistivity profiles, and a consistent to fluctuating sonic profile (Enclosure 23). The gamma and resistivity log profiles are similar to those of the underlying Andrew / Lower Balmoral stratigraphy, whereas sonic values decrease uphole into this unit. It is up to approximately 450' thick.

Cuttings describe this unit as predominantly silty shale / mudstone, moderately fissile, mid / dark grey to brown, non- to slightly calcareous, finely pyritic, with carbonaceous fragments. Sands and limestones do occur, but are rare.

Observations

This unit has is described in cuttings as mudstone / shale, but typically has low gamma values, and is therefore interpreted as being relatively silt-rich. The monotonous gamma and resistivity profiles prevent further subdivision of the unit on log character. There is no recognisable change in log character between the seismically-defined upper (transparent) and lower (downlapping, discontinuous) sub-units. This is consistent with core recovered from the interval in the Ninian area (well 211/29-1, section 3.5.4), which implied monotonous deposition by low concentration turbidity currents.

Conclusions

The Upper Balmoral sequence comprises a more monotonous, generally more argillaceous succession than the underlying Andrew / Lower Balmoral sequences. Basinward downlapping reflectors indicate margin derived sedimentation, and the uphole decrease in sonic values indicates fining-up. This suggests relative retrogradation of the depositional systems. Regional seismic lines demonstrate that the Upper Balmoral Sequence thickens towards the basin margin, onlapping the subjacent Andrew / Lower Balmoral unit at a progressively higher angle landwards, and ultimately onlapping onto the East Shetland Platform margin (section 3.5.4). It is impossible to differentiate between the Andrew / Lower Balmoral and Upper Balmoral units in a distal location on regional seismic lines.

The sharp decrease in sediment calibre during the Upper Balmoral sequence is recognised throughout the North Sea (e.g. Knox et al., 1981; Mudge & Copestake, 1992a,b). In
contrast to the overlying Sele sequence, the Upper Balmoral sequence is fully marine (Mudge & Copestake, 1992a, b).

4.8 The Forties / Sele and Balder sequences

As noted earlier, the Sele and Forties sequences cannot be differentiated in the East Shetland Basin. Well and seismic data suggests that the Forties / Sele sequences comprise a prograding clinoform succession which can be considered as one genetic unit. This prograding succession is here termed the Ninian delta. The full distribution of the unit is described in chapter 3, but the unit is defined below.

4.8.1 The Ninian delta

Age: Mid- to late Thanetian

<table>
<thead>
<tr>
<th>Name</th>
<th>A Shell / Esso term (e.g. Wensrich et al., 1991)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well type section</td>
<td>3/3-2 (Enclosure 15)</td>
</tr>
<tr>
<td>Well reference sections</td>
<td>Proximal position: 3/1-1, 3/11-1 (Enclosure 16)</td>
</tr>
<tr>
<td></td>
<td>Distal: 3/2-5, 3/3-8 (Enclosure 15), 211/27-7 (Enclosure 14)</td>
</tr>
<tr>
<td>Lithology</td>
<td>The delta displays a broadly coarsening up profile, from predominantly claystones and siltstones, becoming sandy uphole. However, this simple character varies significantly, from sandy (e.g. well 3/3-8), to heterolithic (e.g. 211/27-7), or predominantly silty.</td>
</tr>
<tr>
<td>Boundaries</td>
<td>The base of the delta is generally marked by decreasing gamma log values (commonly sharp), and a slight increase in the sonic and resistivity logs. Logs at the base of the delta generally display more 'ratty' profiles than the silts of the underlying Upper Balmoral sequence. The upper boundary is marked by a distinctive gamma / sonic high. The sonic break can be very sharp (e.g. well 3/2-5).</td>
</tr>
<tr>
<td>Distribution</td>
<td>The delta can be defined from block 3/17 north to block 211/21, but it onlaps the underlying sequences to the west. It may correlate with a thin, silty sequence further west. To the SW, the delta tapers in blocks 3/17 and 3/22. The delta onlaps the regional slope of the basin northwards, and downlaps to the east.</td>
</tr>
<tr>
<td>Biostratigraphy</td>
<td>Detailed biostratigraphic analyses are rare in the Paleocene interval in the</td>
</tr>
</tbody>
</table>
area, but probably of Sele sequence age (Mudge & Copestake, 1992b).

**Age**

Mid to late Thanetian.

Enclosures 14 to 21 illustrate the lateral variation of the delta in the East Shetland Basin.

### 4.8.2 Ninian delta clinoforms

#### Seismic Data

This sub-unit predominantly downlaps and occasionally onlaps or bidirectionally downlaps the Upper Balmoral sequence (Figure 4.4). The boundary with the overlying sub-unit is characterised by toplap. The clinoforms pass asymptotically to the east into reflectors with a mounded, chaotic seismic character and which mainly downlap to the east. Individual clinoforms can vary significantly in continuity, and are relatively transparent and less steeply inclined in the middle of the northern survey (Enclosure 25).

The seismic cosets are up to 200ms thick (600 feet), terminating upwards in 'topsets' or occasionally truncated foresets. Time and horizon slices generated through the clinoforms demonstrate the existence of two sets of concentric strikes (Figure 4.5a, b), termed here composite lobes. The boundary between the two composite lobes can be identified on vertical seismic, and marks a change in the angle and amplitude of the foresets (Enclosure 25). This is coincident with a marked change in the differential compaction of the interval (Figures 4.6 & 4.7). The style of the onlap of the younger lobe is examined in section 4.6.2. No evidence of channels or radial bars was observed in the seismic data.

#### Well Data

The uphole transition into this unit is consistently marked by a fall in the gamma profile (either discrete or gradual) and by distinct increases in the sonic and resistivity profiles (Enclosure 23, Figure 4.8b). The unit is lithologically heterogeneous, varying from predominantly shaley to largely silt or sand. When sand is present in the unit, it is easily distinguished from the underlying Upper Balmoral sequence. The log profiles of the sands are 'boxcar' in character, in contrast to those of the Andrew / Lower Balmoral sequences.
Figure 4.4. Crossline 280 (X280). Strike line through the northern seismic survey at the level of the Ninian delta. Note the bidirectional downlapping occurring onto the underlying Upper Balmoral surface (in orange) which could be interpreted as the resulting from slumping or sliding. See Figure 4.1b for orientation.
Figure 4.5. Horizon slices through the Ninian clinoforms from (a) the northern and (b) the southern seismic surveys. Each is a synthetic seismic plane (see Figure 4.2) generated at 140ms below the top Balder surface, and cutting through the clinoform interval. The changing strike of the intersected clinoforms in the northern survey highlights lobe switching. Compare with the top Balder surface (Figures 4.6, 4.7) which demonstrates the differential compaction at the updip edge of the lobes.
Cutting samples describe the sandstones as poorly consolidated, moderately mature (sub-rounded to rounded), with occasional white calcareous matrix. Grain size descriptions vary from poorly sorted (fine to coarse), to moderately sorted (very fine to fine grained; fine to medium grained). Mudstones are silty, medium grey, occasionally lignitic.

4.8.3 Ninian delta 'topsets'

Seismic Data

The delta 'topsets' are defined on 3D seismic data by subparallel, subhorizontal seismic reflectors of relatively low amplitude. The 'topset' reflectors downlap and onlap against the subjacent clinoform unit. The 'topsets' display clearly aggradational (subparallel) stacking, although over the area of the 3D survey, very shallow inclinations may not be identifiable.

Detailed mapping shows numerous high-angle normal and reverse faults, of relatively small throw dissecting the 'topset' and Balder intervals. The faults dominantly occur in structurally high areas, subparallel to strike, and only penetrate the immediately adjacent stratigraphy (Enclosure 25).

Well Data

The delta 'topsets' are predominately sandy with consistently occurring, sharply defined high gamma mudstones in the Ninian area. The upper boundary with the Balder sequence was defined at the base of the distinctive "bowed" log profile as seen on gamma, sonic, and resistivity logs (e.g. Mudge & Copestake, 1992b). Well-to-seismic correlation demonstrates that the lower boundary with the underlying (seismically defined) clinoforms does not have a representative log pick. Where the underlying clinoform strata are argillaceous, the unit is generally characterised by an uphole divergence of the gamma and sonic profiles (resistivity logs show no consistent trend), i.e. cleaning-up. Where the underlying strata are arenaceous, the boundary can not be identified on logs (Figures 4.8a, b).

Cuttings descriptions of sands range from moderately to very poorly sorted; pale grey to green, and generally poorly consolidated with some calcareous matrices. Grain sizes are predominantly medium to coarse, with occasional granules or pebbles (e.g. well 3/2-4:
Figure 4.6. (a) the top Upper Balmoral and (b) the top Balder horizons in the northern survey. Note the mounding of the top Balder surface with respect to the base of the interval. The orientation of the mounding is oblique to the strike of the Upper Balmoral surface. The mounding is interpreted to be due to differentiation compaction at the intersection of lobes 1 and 2. Note that the survey (Figure 4.7) are oriented at 36° to each other, and that they overlap (Encs. 30 & 31). Compare with Figure 4.5a. The penetration of the wells are marked.
Figure 4.7. (a) the top Upper Balmoral and (b) the top Balder horizons in the southern survey (compare with Figure 4.6). The mounding on the top Balder surface in this survey occurs almost directly over the crest of the underlying Upper Balmoral high, unlike the northern survey. The high at top Balder level is more pronounced than on the top Upper Balmoral surface. Comparison with Figure 4.5b suggests that this may be due to differential compaction.

For location, see Enclosures 31 / 32.
Figure 4.8a. Seismic line joining Ninian exploration wells. Equivalent depth section & well correlation in Figure 4.8b. For orientation of line, see Figure 3.1b. For clarity, only well 3/3-9 is displayed.
Figure 4.8b. Correlation of Ninian wells. Compare with equivalent seismic line, Figure 4.8a. For orientation, see Figure 4.1b. Annotation at left hand side (and solid lines) is the sequence interpretation of this study. Annotation at right hand side (and broken lines) is a lithostratigraphic interpretation, after Mudge & Copestake (1992b). Solid lines in clinoform interval taken from 3D seismic correlation. Dotted line of Dornoch interval approximately follows the lobe 1 / lobe 2 boundary.
rhyolite, quartz and gneiss pebbles); and from subrounded to subangular. Anhydritic and extrusive volcanic fragments occur. Interbedded mudstones are varicoloured, moderately fissile, with variable silt content. Limestones and lignites occur rarely.

4.8.4 Well 3/3-11, core 1, 4640' to 4689'

49' of core was recovered from well 3/3-11 over the Sele / Balder boundary (Figure 4.9). This is the only core retrieved from the Sele and Balder intervals in the East Shetland Basin.

Uppermost Sele sequence (delta 'topsets')

The top of the Sele sequence is a medium to coarse grained sand with floating pebbles, granules, calcareous concretions and clay clasts a half to one inch in diameter. Vague subhorizontal laminations are preserved in the sands (4689' [base] to 4680'); no other primary bedding structures were observed. Over a 1' interval, the medium / coarse sands fine up and are abruptly overlain by a thick volcanogenic bed (finely laminated red tuffaceous claystone; 4680' to 4676'), containing a fine sand bed. The tuff becomes cream coloured upwards (top 3"), and it is overlain by about 1' of fine sand. The boundary between the topmost tuffaceous bed and the overlying sand is obscured in the core (covered by resin), but approximately at the boundary (± 1/2") subrounded igneous pebbles occur, up to 2" long (longest axis), and a clay clast approximately 3" in length (Figure 4.10). The tuffaceous clays correspond to a peak on the gamma log.

4.8.5 Balder Sequence

Age: Late Thanetian to early Ypresian

Seismic Data

The Balder sequence generates two high amplitude 'tramline' reflectors which are strong enough to easily identified on regional seismic data. The upper boundary is characterised by the occasional downlap of the overlying post-Balder strata. The lower boundary is not marked by a distinctive change in reflector dip, but the underlying 'topset' reflectors tend to be of slightly lower amplitude than the Balder reflectors in the Ninian 3D data.
Figure 4.9. Graphic log of core 2, well 3/3-11. The Sele - Balder sequence boundary picked at the gamma high from composite log. Note that the interval 4672' to 4689' was encased in resin & could not be closely examined. See text for discussion.
Generation of a seismic horizon parallel to bedding, within the Balder interval (a time slice) indicates no significant amplitude variation, and reveals no information of geological significance. There was no evidence of patterns parallel to or oblique to dip which could have be interpreted as channels, beaches, barriers, etc..

**Well Data**

The Balder sequence predominantly comprises claystones and siltstones interbedded with varicoloured tuffs. It displays a distinctive "bowed" log character on gamma, sonic and resistivity logs, commonly with an intermediate gamma high. This log pattern is regionally consistent, but can have significant internal variation. The top of the unit is picked at the top gamma high nearest the sonic peak.

**Core Data**

The lower section of the cored Balder interval in well 3/3-11 consists of finely laminated silty tuffs grading to claystones (Figure 4.11; =4675' - 4660'). These are fissile to very fissile, with some soft sediment deformation. The upper two thirds of the cored interval (4660' to 4640' [top]) becomes more massive, with a reduced clay content. Soles are generally sharp, whereas bed tops are gradational. The uphole change to less fissile silts coincides with a rise in the resistivity and sonic logs (4660'; see inset, Figure 4.9). The silt proportion gradually increases above this point, and bioturbation becomes evident. Inversely graded beds occurred at one horizon.

These graded, stratified silts fall within the D2.1 classification of Pickering *et al.* (1989), indicating deposition by low-concentration turbidity currents. Local inverse grading implies more complex flow processes.

**4.8.6 Observations on the Forties / Sele and Balder sequences**

Analysis of the log character and cuttings from the clinoform interval indicates a range of physical maturities. Grain sizes up to granule and pebble grade indicate that high energy conditions were experienced during sediment transport. The occurrence of lignites (as opposed to carbonaceous material) suggests proximity to land - although no *in situ* coals
Figure 4.10. Detail of transgressive surface at 4676', well 3/3-11. Core preservation good, save that lowermost 17' of core is encased in resin, as in this photo. The lower half of the photo shows the top of the tuff sequence changing uphole from grey/pink to cream. At the top of this unit large pebbles are observed, but these are obscured on the left hand side of the core. A fine sandstone overlies the transgressive surface. Black/white bars at left hand side are 3cm. See text for discussion.
Figure 4.11. Well 3/3-11, core 2. Photo (a) (4652' to 4664') shows the change from relatively condensed fissile shales to more lithified, silty laminasets and beds. The change of lithology at 4658' corresponds to a rise in the sonic log (see Figure 4.9 inset). (b) The silt dominated lithologies demonstrate small-scale dewatering structures, coarsening- and fining-up beds, erosional surfaces, bedding up to c. 10cm thick, and a repetitive cycle of silty beds followed by thin to thick laminasets. These features are characteristic of low-concentration turbidites. Bioturbation is rare towards the base of the silty unit, but becomes common towards the top, indicating the colonisation of the sea bottom, and by implication a relative decrease in the frequency of depositing flows. Black / white bars on core are 3cm. See text for discussion.
were identified in contrast to the comparable Outer Moray Firth stratigraphy (e.g. Milton et al., 1990). The presence of extensive seismic clinoform 'topsets' indicates water depths up to fair-weather wavebase (approximately 10m). Complex grain size trends are observed, although simple decreasing- (coarsening-) up trends can be identified both within the clinoform sub-unit, and between the seismic (clinoform and subparallel) sub-units.

Seismic strike lines such as shown in Figure 4.4 present the only evidence of mounding in the dataset which might be interpreted as slumping. No faults or characteristic patterns show clearly in dip seismic section to unambiguously support this interpretation, although seismic resolution is likely to be too poor to pick out many discrete, small slump or slide features. However, slumps and slides are common in fine grained deltas in similar grain size domains to that seen in the pro-delta, where the mounding is observed in the strike seismic sections. It is therefore possible that such movements did effect the Ninian delta, but without greater seismic resolution, the extent of down slope mass movement can not be quantified.

A seismic isochron of both seismic sub-units combined indicates that the stratigraphy thickens into the Jurassic hanging wall (Figure 4.12). This simple pattern is complicated by differences in differential compaction at the boundary of the two lobes (Figure 4.6, 4.7). However, the thickening of the Sele / Balder interval across the Jurassic fault crest may indicate that this structural lineament separated depocentres during the early phase of delta build-out. This is consistent with the position of the regional depocentre which lies between Jurassic fault trends (section 3.5.6).

The distinctive log character of the Balder allows it to be correlated throughout the North Sea (e.g. Mudge & Copestake, 1992a, b). The "bowed" log profile is caused by the occurrence of a tuff, indicating contemporaneous volcanism, and probably deriving from eruptions west of Shetland (Knox & Morton, 1988). Minor faulting in the Balder horizon is also common in the Outer Moray Firth (unpublished work) and in the post-Paleocene succession of the North Sea (Cartwright, 1994). Given the location of the faulting on structural highs, their high angles and small throws, the confinement of faulting to the Balder interval, the fact that the Balder is a permeability barrier, and the underlying strata are overpressured, it seems likely that faulting was caused by mechanical failure upon overpressuring.
Figure 4.12. Isochron of the Forties to Balder sequences interval from (a) the northern and (b) the southern surveys. Composite figures of the Ninian delta isochrons (colour) superimposed upon the structural contours of the top Upper Balmoral surfaces (in time). The thickness of the isochron is represented by a colour change from yellow to red (see key). The delta isochron clearly increases in thickness to the east of the high, probably indicating an accommodation control on deposition. This trend is seen along the length of the depositional slope in the northern survey (a), but not towards the south of the southern survey (b). Comparison with Figures 4.5a & b suggests that sediment was sourced from the southwest of the northern survey, so accommodation may have only been limiting where sediment supply was high.

Compare with Enclosures 30 & 31.
4.8.7 Conclusions

The clinoform seismic geometries seen in the 3D seismic data are predominantly progradational oblique, with no evidence of sigmoidal or retrogradational stacking (Enclosure 25). These reflection patterns indicate relatively rapid progradation without the coeval creation of significant accommodation space. Mass movement of un lithified or semi-lithified sediment (slumps, slides) is likely to have occurred, particularly in the prodelta. The fact that accommodation space at the top of the clinoforms fell to zero suggests that the top of the clinoforms were formed at or near wavebase. Seismic evidence thus indicates an overall shallowing-up trend from relatively deep water deposition to wavebase over a 1000' section. Evidence presented in chapter 5 indicates that contemporaneous erosion took place updip at least to a limited extent - there is no data to indicate significant erosion of the northern East Shetland Platform during deposition of the Ninian delta.

The interpretation of this sequence is of a deep water, shelf-margin delta (Suter & Berryhill, 1985). The coarsening-up log character corresponds with a increasing proportion of terrestrial flora, indicating an increasingly nearshore environment (Mudge & Copestake, 1992b). The presence of anhydrite and the increased proportion of lignitic material also supports this interpretation. No regressive surface of marine erosion (sensu Posamentier et al., 1992) is observed at the base of the Sele sequence which might be used as an alternative to a sequence boundary: the base of the Ninian delta thus can not strictly be defined as a sequence boundary. The possible sequence stratigraphic interpretations of the delta and the 'topsets' are discussed in detail in section 4.10.
Discussion

This rest of this chapter considers various aspects of the delta as observed on 3D seismic data. As noted earlier, there is only one study of the Sele sequence in the literature (Parker, 1975). This is rectified here with a discussion of the delta processes, a consideration of the interpretation of the delta 'topset' sands and abandonment, and finally a discussion of the data in light of some recent high-resolution work on Quaternary shelf-margin deltas.

4.9 Discussion of processes

4.9.1 Delta depositional processes

Basinal energy regime

Deltas occur at the entry point of a river system into an open body of water. The rapid decrease in velocity and flow competence of the previously confined current results in the deposition of the entrained sediment load. The sediment load comprises a bedload which is generally deposited in the immediate vicinity of the river mouth, and a suspended load which disperses more distally (Figure 4.13). The external delta morphology and the position of the major deposition elements are strongly influenced by the processes acting at the delta front: the volume and variability of fluvial discharge, the tidal range and the wave energy (Wright & Coleman, 1974; Wright et al., 1980; Kostaschuk, 1985). These three factors have dominated modern delta classifications (e.g. Galloway, 1975; Figure 4.14a).

During the Forties / Sele sequences, the North Sea was enclosed (King, 1993), with anoxic conditions existing throughout the basin. The dominance of diatoms indicates freshwater input had reduced the salinity of the basin (Mudge & Copestake, 1992b). These data suggest that any oceanic connection was negligible and tidal influence is likely to have been minimal. The position of the coastline during Sele times indicates that the width of the Northern North Sea was at maximum half its present width and possibly considerably less (contemporaneous uplift in the Norwegian North Sea was not significant; Den Hartog Jager et al., 1993). Climatological data (e.g. Frakes, 1979) indicate that NW Europe resided in subtropical latitudes, so the basin may have experienced considerable rainfall, and / or tropical storms. From the above evidence - limited fetch, relatively deep water, the
Figure 4.13. Deposition of bedload and suspended load at the river mouth. The relative density of the sediment-laden river water & basinal waters strongly influences whether the entrained sediment load is deposited proximal to the river mouth (A), carries on into the basin as a coherent flow (B), or deposited more distally (C). From Fisher, 1969; originally from Bates, 1953.
Figure 4.14. Modern delta classifications discriminated by (a) the relative power of sediment dispersal processes (after Galloway, 1975) and by (b) sediment input (after Orton, 1988). Numbered deltas relate to general examples; lettered deltas are of similar size to the Ninian delta & are listed in Table 6.2 (page 228). Note that the classification of a few deltas (6,7,8) varies between the authors.
isolation and position of the basin, the paleogeographic setting - it is inferred that wave activity in the basin was probably limited. There is no evidence to assess the influence of storm activity in the basin.

In the Ninian delta, the preservation of composite lobes indicates preservation of a delta-front depositional regime that was sourced by shifting point sources. The dimensions of the composite lobes in the 3D dataset are comparable in size to lobes described elsewhere (e.g. Sydow & Roberts, 1994; Figure 4.15). The fact that no significant reworking of sediment input has taken place is consistent with the interpretation of a fluvial-dominated regime, as would be expected in a restricted basin. Furthermore, Suter & Berryhill (1985) consider that oblique parallel to complex sigmoid-oblique seismic reflectors (as Ninian) to be characteristic of fluvial-dominated deltas. Lastly, avulsion is most typical of river- or river/wave-dominated deltas; wave-dominated deltas tend to be reworked and tide-dominated deltas often occur in narrow basins where lobe development is restricted (Elliott, 1986).

The influence of subsidence on the delta formation cannot be directly measured, but from the occurrence of the delta depocentre between Jurassic faults (Figure 3.15), and the change in seismic character indicating active slope processes, it can be inferred that subsidence played a role in creating accommodation space during the Forties / Sele and Balder intervals. The very significant progradation of the delta obviously supports the interpretation of accommodation space defining sedimentation patterns, and so any local variations due to subsidence are likely to have resulted in sediment thickness changes.

**Consideration of supply factors**

A description of the basinal energy regime can be made, but many factors in fact influence delta development. Elliot (1986) considered that all the following were important influences on deltas: the shape, size, bathymetry, and energy regime of the basin; its subsidence and tectonic evolution, and sea-level; the salinity, relative density of the fluvial and basin waters; the hinterland characteristics; and climate, which primarily affects the nature of the delta plain. However it is difficult to determine many of these factors in ancient successions, and consequently recent work has focused on examining factors which influence modern deltas, but which can also be quantified in the rock record.
Figure 4.15. Lobe distribution within unit pro 10 of Sydow & Roberts (1994). See text for discussion. Upper map shows location of the Lagnappe delta, and the distribution of buried fluvial deposits updip.
Supply parameters can be recognised in ancient successions. Orton & Reading (1993) evaluated the variability of deltaic processes in terms of grain size and sediment calibre. These two variables are relatively easy to record in the subsurface, and they influence a) the gradient & channel pattern of the fluvial system on the delta plain; b) the mixing behaviour at the river mouth; c) the type of shoreline, dispersive or reflective, and thus its response to wave and tidal energy; and d) the deformation processes at the delta front. Complementary work has been done in extending delta classification systems to include the effects of sediment calibre (e.g. Orton, 1988; Figure 4.14b). The following section therefore focuses on the describing the Ninian delta in terms of the recognisable supply parameters.

4.9.2 Depositional processes in the Ninian delta

Delta lobes

In the 3D seismic data, two lobes can be clearly defined on horizontal and vertical seismic data (Enclosure 25). The sediment calibre of the lobes is observed to change as defined on logs (e.g. Figure 4.8b), and by the differential compaction observed at top Balder level (Figure 4.6). The boundary between the two composite lobes is disconformable, as demonstrated by the angular discontinuity at the boundary on horizon slices (Figure 4.5) and the changing reflector geometries on vertical seismic (Enclosure 25).

In the north of the survey (e.g. Inline I400, Enclosure 25a), the youngest clinoforms downlap onto hummocky reflectors at the base of the lobe 2 sequence. The heterogeneous nature of the log profiles over these intervals, and the bidirectional dip of the reflectors at the foot of the foresets suggests that the hummocky deposits are gravity flow deposits, which could have been sourced either laterally, or alternatively across the shelf edge left by the abandonment of the previous lobe. This is unusual in comparison to the rest of the seismic survey. Furthermore, delta front deformation features are on the whole more common in finer grained deltas (Orton & Reading, 1993). In comparison, the youngest prograding clinoforms of lobe 2 to the south (Inline I500, Enclosure 25c) advance over a more gentle lobe 1 profile, preserving well-defined clinoforms with no underlying hummocky strata. Transitional between these two depositional styles (e.g. I450, Enclosure 25b), clinoforms are developed in limited accommodation space above lobe 1 (Enclosure 25b, c).
Thus accommodation space is observed to increase with distance from the lobe 1 depocentre (no evidence of distributory channels was observed on seismic), but it is considered that the depositional gradient was more important in defining the styles of progradation of younger lobe. The observed (post-compaction) bathymetry implies that further from the lobe 1 depocentre, lobe 2 progradation took place into shallower water, and this corresponds with a change to more coherent clinoform geometries. In contrast, in the north of the survey a relative steep depositional profile is preserved, which is associated with discontinuous deposition of the lower lobe 2 sediments.

Between deposition of the two observed lobes, it is suggested that progradation took place outside the area of the dataset to a greater or lesser extent; the time interval separating progradation of the two lobes could be vary from a matter of hours to hundreds of years. Time and horizon slices demonstrate that (seismic-scale) deposition at the lobe boundary took place diachronously, implying that a hiatal interval of varying duration (increasing to the north) separates the two lobes. Progradation of the lobe 2 clinoforms occurred only after the deposition of the chaotic lower reflectors.

The above explanation is however complicated by the break of slope over the underlying Jurassic fault block. The break of slope probably influenced the change in reflector character to the north of the survey, but the relative lack of similar hummocky reflectors in lines to the south suggests the influence was only marginal.

**Delta Front Processes**

Where the depth of the receiving basin is deep enough to allow the formation of foresets, the gradient of the foreset (or clinoform) is related to the sediment grain size, the efficiency of the dispersal processes on the delta front (e.g. Prior & Bornhold, 1988), and the rates of formation of accommodation space relative to the lateral rates of sediment deposition (Cant, 1989). Continuous supply of sediment to the delta front results in progressively increasing slopes until they can no longer be maintained (angle of initial yield). At this point, slope failure occurs, resulting in the mass flow of sediment downslope, and reduction of the failed slope to a stable angle (the angle to repose) (Figure 4.16).

Foreset sedimentation is dominated by gravity-driven mass flows, either as hyperpycnal flows during river-floods (Prior & Bornhold, 1990), or ebb of storm-driven sediment-
Figure 4.16. Block diagram illustrating change in the angle of the delta depositional profile with increasing distance from the distributory mouth. Any wave power travelling across the shallow, the dissipative shelf will be attenuated. In contrast, the steeper shelf profile is more reflective, and basinal wave energy will result in degradation of the steep depositional profile. Compare with depositional profiles imaged on 3D Inlines 400, 450, 500, & 550 (Enclosure 25). See section 3.7 for further discussion. North represents direction of North in northern Ninian 3D survey.
laden flows (Massari & Parea, 1990). Processes of delta front sedimentation are complicated, but include translational or rotational slumps or slides; fall of debris; high density debris flows; high and low density turbidites; and hemipelagic sedimentation (see Orton & Reading, 1993). Offshore transport of sand is limited (sands of the Bella Coola delta front extend only 3-5km from the river mouth; Prior & Bornhold, 1988); and the occurrence of only even minor amounts of clay in sand or gravel delta can significantly increases downslope sediment diffusion and failure on the upper delta slope (Colella et al., 1987).

The processes driving foreset progradation in the Ninian delta are not possible to determine from the dataset, but a number of observations can be made about the gross development of the delta in the Ninian area. Comparison of Enclosure 25a to d implies that progradation only occurred in the north after slope degradation had reduced the angle and height of the slope break. The data suggests that the development of the new delta lobe was influenced by the bathymetric profile of the abandoned lobe. Distal to the previous depocentre, the available accommodation space increased. Furthermore the depositional profile of the abandoned lobe decreased, and the shallower depositional profile was more dissipative (Figure 4.16; Orton & Reading, 1993). The effects of any wave energy would thus be subdued, encouraging the preservation of coherent clinoforms.

4.9.3 Summary of delta processes

The extra dimension available with 3D seismic data - horizon slices - gives an insight into lobe evolution that is not available from 2D data; the strike variations in lobe architecture cannot easily be appreciated on vertical seismic alone. This study is thus an important addition to the published literature.

In the Ninian 3D dataset, small scale erosion degraded the steep, reflective depositional profile in the north of the survey. Deposition of clinoform reflectors was only re-established in this area after hummocky (slump or slide) reflectors were deposited, suggesting the angle of the slope was too great for the preservation of coherent clinoforms. Progradation advanced from the SW of the lobe (Figure 4.5a), so it is not possible to ascertain whether progradation resumed in the north of the survey because of, or in spite of, the reduction in slope relief. In the south of the survey, large, coherent clinoforms are observed, and little evidence of slumping. The shallower depositional slope was thus too
shallow to cause significant deformation on the delta-front; the more dissipative depositional profile would also have subdued any wave energy in the basin.

The nature of the discontinuity between the two lobes cannot be defined unambiguously with the available seismic and well log evidence. It is considered that the boundary is probably both erosional and hiatal, with these two end-members co-existing along strike. Distinguishing between the causes of avulsion (e.g. tectonics, climate change, relative sea-level rise) was not possible with the dataset. However, the reflector patterns seen at the boundary of the two lobes are similar to those observed in Tesson et al., (1993), and which were attributed to sea-level fluctuations (Figure 4.17). In contrast, Suter et al. (1987) noted that high-frequency deltaic cycles could be produced autocyclusically. The latter interpretation is consistent with the absence of evidence for base-level fluctuation in this study. Finally, Reading (1986) considered that the interplay of physical processes is probably overstressed, and that sediment grain size is probably of greater significance in shaping delta processes than is generally recognised.

The interpretation of a fluvial-dominated delta-front regime contrasts with that of Galloway et al. (1993) who stated that "evidence of late Paleocene tidal & wave reworking... supports the assumption that the Paleocene, like the modern North Sea, was characterised by high marine energy flux". Galloway's argument is advanced without any supporting data, but the difference between the modern wide, relatively shallow, open-marine shelf-dominated North Sea and that of the Paleocene North Sea as described above (with limited fetch, relatively deep water, isolated, anoxic; a large freshwater input and vastly greater sediment flux) supports the interpretation put forward here.

4.10 Depositional environment of the delta 'topset' sands

4.10.1 Introduction

The Ninian delta 'topset' sands are the topmost, coarsening-up unit of the delta (the Dornoch Formation of Mudge & Copestake, 1992b - Enclosure 23; the topsets of Den Hartog Jager et al., 1993). The term 'topset' is used here for simplicity, for although their genesis is ambiguous, the preferred interpretation is that they are related to the underlying Ninian delta, not the overlying Balder sequence. Understanding the genesis of the 'topset' sands is important for assessing the evolution and character of the Ninian delta. The
Figure 4.17. Interpretation of a eustatic sea-level control on the internal discontinuities within a clinoform deltaic succession. From Tesson et al. (1993).
number of sequences observed in the Ninian delta area has implications for correlation updip in the Bressay area (Chapter 5). The interpretation of the 'topsets' is also significant for predicting the quality and distribution of any sands downdip. Unfortunately, the nature of the sands is ambiguous, and alternative descriptions each have implications for the interpretation of the ultimate transgression of the delta.

The succession in the 3/3-11 core (4km northeast of the 3D survey) is described in sections 4.8.4 and 4.8.5 (Figure 4.9).

4.10.2 Upper Ninian sands as delta plain deposits

Delta plain deposits are generally parallel / divergent aggradational strata which may directly downlap the delta front facies. They may alternatively be separated from the underlying inclined progradational clinoforms by a fluvial bypass or erosional toplap discontinuity. Such a description closely fits the observed Ninian field 3D data, and so the interpretation of the uppermost delta sands (as seen at the base of core 3/3-11) as delta plain deposits is considered most likely.

The number, relative size, and distribution of distributory channels control sedimentation on the delta plain; although a delta plain may have just one channel, more commonly there are several. The character of channel patterns allow them to be divided into four classes, according to bedload (Orton & Reading, 1993 after Schumm, 1981; Figure 4.18). The classes are 1) very high bedload channels (>50% bedload); 2) bedload channels (11-50% bedload) 3) mixed load channels (3-11% bedload); and 4) suspended load or dissolved load channels (<3% bedload). Grain size is a practical way of approximating bedload in ancient sequences, although it does not exactly correlate with Schumm's hydraulic definition of bedload: in fluvial systems with high discharge, the sediment calibre of the bedload will be higher (Orton & Reading, 1993).

The amount of bedload accumulating on the delta plain depends on the stability of the channel banks. For instance, in the Klinaklini River delta, 72% of the bedload is retained as topset because channel shifting and channel overflow are very common, whereas the Homathko River, discharging into a nearby fjord, is comparatively stable with only 20% of bedload retained as topset (Syvitski et al., 1988). Both the Klinaklini and Homathko River plains are examples of gravely delta plains. In contrast, in sandy, braided deltas,
Figure 4.18. Schematic diagram illustrating the relationship between grain size and channel pattern on the delta plain. The arrow at the left hand side of the diagram illustrates increasing stream power & sediment load relative to stream power. After Orton & Reading (1993).
although one channel can dominate the delta plain, commonly distributory channels bisect until the delta front is effectively fed by a line source. Lateral migration of the distributory channels tends to be controlled by the volume and regularity of discharge. Rates vary for instance from 10-20m / year (the MacKenzie River; Lapointe, 1990) to 500m / year (the Kosi River; Gohain & Parkash, 1990). In sandy, mixed load delta plains, clay consolidation of the channel banks tends to inhibit channel migration and bifurcation. The frequency of avulsion depends on the rate that levees build above floodplains, and the amount of vegetation (McCarthy et al., 1992).

The topmost sands of the Ninian delta are medium to coarse grained, which from Figure 4.18 implies that the Ninian delta plain channels were probably bedload channels (11-50% bedload). The factors controlling the stability of the delta plain channels can not be quantified in the dataset, however, the clay content of sands observed in core was negligible implying that avulsion and channel migration would have been common. The size of the observed lobes in the 3D dataset (about 5km radius) perhaps suggests a predominantly line source, which would be consistent with the concept of shifting channels. The proportion of the bedload preserved as topsets is difficult to ascertain. However, log evidence of coarsening-up is generally limited to the top of the succession, perhaps again suggesting that much of the bedload was retained as topsets, and was not transported directly to the delta front.

4.10.3 Upper Ninian sands as river mouth deposits

Delta progradation occurs ahead of distributory channels as bedload sands migrate over the prodelta silts and clays to produce channel-mouth bars (Figure 4.19). Dispersal of the fluvial bedload is dependent on the relative buoyancy of the river waters and the receiving basin, the turbulent friction of coalescing flows, and the inertia of the flow (Wright, 1977). Differentiation of such controls in datasets such as used in this study is not possible, but rivers entering relatively deep marine waters are generally buoyancy driven and have Gilbert-type delta fronts (e.g. Wright, 1977). The 'topset' sands could be interpreted as river mouth deposits, but it is unlikely as explained in this section.

Early preservation of river mouth deposits depends on the rates of compactional subsidence, and the intensity and type of marine energy (Figure 4.19). Thus channel-mouth bar sands rapidly subside below effective wave base in muddy river dominated
Potential surface of erosion if basinal processes rework topsets, or subsidence is not great enough to prevent erosion by successive fluvial systems.

Distributory channel mouth bar

Angle of delta-front proportional to grain-size & efficiency of dispersal processes

Sea Level

Delta plain

Delta Front

Topsets

Foresets (clinoforms)

(oversteepening leading to slumping)

= Subsidence & compaction controlling topset preservation potential

FWWB = Fair Weather Wave Base

Figure 4.19. Principal depositional elements of a delta. Rapid subsidence is required in order to preserve delta front depositional facies, as both nearshore currents and the successive fluvial systems can result in removal of delta front sands. Stability of the delta front is related to sediment calibre. Small variations in the clay content of the sediment can dramatically increase delta front deformation. In the Ninian delta, with relatively coarse sediment, significant delta front deformation is not observed (at a seismic scale).
deltas; in wave dominated regimes, channel-mouth bars are extensively reworked by the dominant current; and in areas of strong tidal influence, these sands generally become radially reworked into channel fills and tidal bars. Channel mouth sands pinchout updip and downdip, prodelta sediments thin and fine distally.

The interpretation of the 'topset' sands as river mouth deposits is considered unlikely because with a coarse-grained bedload, early compactional subsidence around the distributory mouth was probably limited (compaction increases with clay content). On the other hand, the delta front environment is considered to be fluvial-dominated (section 4.7.3), so the sediment input may just have swamped the basinal energy regime. The rate of creation of accommodation space is also an important but undefined factor in determining the balance of these influences.

4.10.4 Upper Ninian sands as a transgressive succession

An alternative interpretation is that the topmost, aggradational Sele sands are truly transgressive shelf sands. In this interpretation, transgression of the delta plain took place and maintained equilibrium until rapid Balder transgression ensued. Transgressive stratigraphies can be varied: coarsening-up, fining-up, or mixed (Nummedal & Swift, 1987; Davis & Clifton, 1987). The Ninian delta 'topset' sands are approximately 300' thick, and have little variation in grain-size in the area. Bourgeois (1980) noted that in contrast to the Cretaceous of Western Interior (e.g. Van Wagoner, 1990) thick transgressive sequences are relatively common on the tectonically-active Pacific coast. Bourgeois proposed that the thick transgressive bodies of the Upper Cretaceous Cape Sebastian Sandstone (southwest Oregon) resulted from high sediment flux, due to tectonism. This is similar to the Paleocene of the North Sea. However, the author described a fining-up sequence culminating with laminated very fine sandstones and bioturbated siltstones, so the Cape Sebastian Sandstone is not considered analogous.

A second example of aggrading transgressive offshore sands is the lower Paleozoic Peninsula Formation of South Africa (Hobday & Tankard, 1978). This outcrop demonstrates a very thick (750m) succession attributed to gradual subsidence balanced by sediment supply, leading to a vertical stacking of facies. No significant change took place in water depths until the regime was eventually terminated by marine regression. The vertical build-up of barriers under rising sea-level and high sediment supply conditions
was also described by Bridges (1976). Thus in order to preserve a thick sequence of transgressive sands, a high sediment flux is required to balance any rising sea-level. The sediment supply during the Sele sequence is also comparatively high and terminated by a surface of marine regression. This scenario could therefore result from the rate of sediment accumulation of the Ninian delta 'topsets' keeping up with the creation of accommodation space during early transgression, but subsequently being outpaced and drowned. The interpretation is problematic because if the top Ninian delta sands were a transgressive shelf sequence, it is difficult to explain the occurrence of pebble-grade material at the top of the sequence.

4.10.5 Sequence interpretation of the 'topsets'

The 'topset' sands are not considered to be a transgressive body, but a more exact interpretation of the 'topset' sands cannot be constrained with the available data. Three alternative scenarios are therefore suggested for their genesis. The interval could represent (see also Figure 4.20):

a) a simple progradation and transgression of an erosive, genetically-related shoreface
b) a diachronous 'shingled' shoreface essentially coeval with delta-front deposition
c) an uppermost Sele shoreface separated from the clinoform interval by a sequence boundary and / or ravinement surface.

Without core information over the base of the 'topset' interval, the above scenarios cannot be differentiated. However interpretations a) and b) are the simplest explanations for the origin of the body, and as such are favoured over interpretation c). The alternatives are outlined below.

a) Progradation of an erosive, genetically-related shoreface (Figure 4.20a) occurs when a lack of accommodation space leads to the scouring of the distributory mouth deposits. The predominance of oblique over sigmoid / complex clinoforms in the Ninian 3D (lobe 2, Enclosure 25) suggests that accommodation space was limiting during progradation. Thus the boundary between the 'topsets' (subhorizontal seismic reflectors) and underlying clinoforms in this interpretation would be a discontinuity or marine diastem (sensu Nummedal & Swift, 1987). The two intervals would therefore be genetically
Figure 4.20. Alternative sequence interpretations of the Ninian 'topsets' (after Hart & Plint, 1993). The scenarios are (a) simple progradation and transgression of an erosive, genetically-related shoreface, (b) a diachronous 'shingled' shoreface essentially coeval with delta-front deposition, and (c) an uppermost Sele shoreface separated from the clinoform interval by a sequence boundary and/or ravinement surface. Without data from the base of the 'topset' interval, these possibilities cannot be distinguished. See section 4.10.5.
related, and the 'topset' sands and claystones would be aggradational fluvial or lagoonal sediments preserved in accommodation space created by fluvial grading associated with relative sea-level rise and/or subsidence and compaction elevating the fluvial profile (Leopold & Bull, 1979).

b) Figure 3.17 indicated that the 'topsets', as indicated by the existence of a strong 'tramline' reflector, discontinue before the offlap break of the delta, and possibly immediately updip of the most distal lobe deposition (defining the exact relationship is beyond the resolution of the regional seismic lines; section 3.5.6). As illustrated in Figure 3.18, the data could be interpreted as a (diachronous) 'shingled' shoreface coeval with development of the most distal lobes. Lobe deposition must be coeval with topset sedimentation to some finite extent (Cartwright et al., 1993), and although an accurate assessment of this was not possible in the dataset, the 'topsets' may have acted as conduits for distal lobe deposition.

c) The Ninian 'topset' and clinoform intervals could be genetically unrelated. Two possibilities exist within this scenario: the intervals are separated by either a ravinement surface (e.g. Hart & Plint, 1993), or by a sequence boundary - maximum flooding surface (e.g. Suter et al., 1987; Trincardi & Field, 1990). If either scenario is correct, it implies that the 'topset' and clinoform intervals were deposited by separate depositional pulses into the basin, and are separate sequences. However, discriminating between the two possibilities is not possible without sedimentological evidence from the surface itself.

As noted above, differentiation of the three interpretations for the 'topset' sands cannot be made without further evidence, particularly sedimentological data. However the next two sections consider delta evolution more generally in an attempt to draw conclusions which may be applied to the Ninian delta.
Figure 4.21. Models of coastline transgression by (a) shoreface retreat and (b) in-place drowning (after Swift, 1975a; and Sanders & Kumar, 1975a respectively). Both models were developed for the East Coast U.S.A. Relatively low sedimentation rates and rapid sea level rise favour in-place drowning. See section 4.11 for further discussion.
4.11 Delta abandonment

Introduction

There are two accepted mechanisms for the transgression of wave dominated shorelines, developed from studies of the Holocene transgression of the east Coast, U.S.A.. During shoreface retreat (Bruun, 1962; Figure 4.21a), sea-level causes sediment erosion from the upper shoreface and emplacement occurs either by storms in the lower shoreface, or washed over into a back-barrier environment. The record of the advancing lower shoreface as it transgresses is termed the shoreface erosion surface, or a ravinement surface (Swift, 1968). The extent of erosion depends on the rates of sea-level rise and subsidence. When erosion is limited a coarsening-up sequence is preserved below the erosional surface reflecting infilling of the lagoon by increasingly proximal washover sands.

During in-place drowning (Sanders & Kumar, 1975a,b; Figure 4.21b), the barrier remains in place until sea-level rises sufficient to drown it, and there is a sudden landward jump in the position of the shoreline. In this mechanism, the breaker zone therefore moves rapidly over the shelf rather than progressively reworking it as in shoreface retreat. Conditions of relatively rapid sea-level change and low sediment supply favour in-place drowning, whereas the converse favours shoreface retreat, although the gradient and structure of the pre-transgression depositional profile are also influential.

Ninian delta abandonment

The occurrence of out-sized clasts at the boundary between the volcanics and overlying sand (4676'; Figure 4.10) indicates a depositional break or hiatus. The overlying bioturbated, low-concentration turbidite flows imply a low energy, distal marine environment - a clear deepening of facies from the underlying coarse sands. The pebble horizon could thus represent a transgressive lag or ravinement surface (Figure 4.21a). This interpretation implies that encroachment of the shoreface upon the deltaic margin brought sufficiently high energy conditions to transport pebbles, or that beach conditions were established. Concomitant erosion - possibly significant - is likely to have occurred into the underlying soft volcanic clays (Bruun, 1962). A very sharp change in the sonic log character (a sonic 'spike') is observed at this boundary, which becomes more pronounced to the west of the Ninian field (blocks 3/2 and 3/1; section 3.5.6). The strength of the sonic
peak may indicate strong cementation at this boundary; the log character generally is consistent with the suggestion of erosion (ravinement), increasing to the west, but ultimately decreasing to both the west and east.

The alternative interpretation is that the pebble-grade material came into the system at times of high fluvial outwash (e.g. Prior & Bornhold, 1988), and that the nearshore environments were transgressed by in-place drowning. The fall off in clastic sediment recorded at the top of the 3/3-11 core suggests a relative increase in accommodation space before complete transgression, and the apparent lack of overlying shoreface deposition implies a relatively rapid transgression. Both pieces of evidence favour an in-place drowning interpretation.

The preservation of the volcanogenic succession, indicates that erosion was probably not great. Fischer (1961) considered that the preservation potential of sequences is a function of the depth of shoreface erosion as transgression progressed, whilst Belknap & Kraft (1981) cited that rate of relative sea-level rise as being most important to preservation. These factors are obviously linked (erosion will be greater during slower transgression, if the erosive energy of the transgressing system remains constant). In the East Shetland Basin, volcanism is contemporaneous with the onset of significant volcanism in the northeast Atlantic, the initiation of which is thought to have led to the collapse of the basin margin uplift (Knox & Morton, 1988; Brodie & White, 1993). Thus preservation of the volcanogenic stratigraphy was probably a function of relatively rapid transgression. This is again consistent with an interpretation of in-place drowning.

In each of shoreface retreat and in-place drowning, the preserved transgressive deposits are generally thin, as observed in core 3/3-11. The abandonment of the delta during shoreface retreat or in-place drowning would fit with an interpretation of the top delta sands as delta plain or shoreline deposits. The 'topset' sands would thus be coeval with deposition of the distal lobes on the delta front (Figure 3.18b). This is discussed further in following sections. As noted, the interpretation of the top delta sands as a transgressive succession does not easily explain the core data.
4.12 Ninian delta analogues

The Ninian delta comprises a succession of shoaling-up, deep water deltaic deposits occurring basinward of the tectonic shelf in the North Sea basin, and as such can be defined as a shelf-margin delta (sensu Suter & Berryhill, 1985). A considerable body of high-resolution research exists on shelf margin deltas, which was principally undertaken on Quaternary shelf-margin deltas off Italy (e.g. Trincardi & Field, 1990), the Rhône continental shelf (e.g. Tesson et al., 1993) & the Gulf of Mexico (e.g. Suter & Berryhill, 1985; Suter et al., 1987; Kindinger, 1988; Sydow & Roberts, 1994). The geological setting of these Quaternary deltas clearly differs significantly from the Paleocene of the North Sea - deposition in most of the described deltas was driven by rapid, glacio-eustatic sea-level fluctuations, and occurred on passive continental margins, i.e. in open sea as opposed in a land locked sea in the case of the East Shetland Basin at the time of Ninian delta progradation. The setting of the deltas described in this section are therefore different from those of the Ninian delta, but the regime at the delta front is supply dominated to a greater or lesser extent in each case, and comparison of the Ninian with the recent work on Quaternary deltas is considered a worthwhile exercise.

Suter & Berryhill (1985) defined the seismic characteristics of shelf-margin deltas from the Late Quaternary of the Gulf of Mexico. Their description of relatively steep clinoform reflectors and chaotic facies (discontinuous, discordant, non-parallel) indicating slumping and sliding as a continuous process during delta build-out could also be applied to the Ninian delta (Figure 4.4; section 4.8.6). An important feature of both the Ninian and shelf-margin deltas is the updip erosion that took place as a result of forced regression as base level dropped.

Sydow and Roberts (1994) described the Lagniappe delta of the West Mississippi - Alabama Shelf (northern Gulf of Mexico) using high-resolution seismic and a continuous core. The Lagniappe delta exhibits tangential oblique clinoform progradation which distally become sigmoid (Figure 4.22). These clinoforms are scoured on their upper surface in a distal position by a trough-like incision, which is infilled with a complex fluvial fill (fill A). At the shelf edge, the fluvial erosion becomes confined to the topsets and intercalates with (apparently feeds) the topsets of small, distal lobes (Figure 4.22). Up-dip, fluvial fill A is strongly erosional, removing most of the deltaic sediments on the mid-shelf (Kindinger, 1988; Figure 4.23). The fill of the trough-like fluvial sequence is variable - horizontal to
Figure 4.22. Annotated seismic profile from the distal, southwestern limit of the Lagniapect delta illustrating the aggradational component in stacking of numerous small progradational clinoform sets, each bounded by an internal toplap (I.T.) surface. Note the thinning of Fill A, and the merging of this facies with distal clinoform sets. From Sydow & Roberts (1994). See Figure 4.15 for inset location.
Figure 4.23. Distribution of buried fluvial deposits updip of & feeding the late Wisconsin (Lagnaipe) delta. The fluvial channels have removed most of the underlying deltaic sediments on the middle shelf (from Kindinger, 1988). This contrasts with the observed fluvial erosion in the North Sea, which is not observed directly updip of the main body of the Ninian delta (R. Anderton, pers. comm.).
Figure 4.24. (a) Dip profile through the axis of the erosional trough showing the prograding clinoforms and the incising overlying fluvial fill. (b) Graphic log of the cored sequence through the Lagniappe delta. Note the coarsening up sequence is abruptly terminated on well data by fluvial Fill A (from Sydow & Roberts, 1994)
steeply inclined, wavy or channel-like strata which become sub-horizontal and more continuous distally.

Log data indicate the fluvial fill to be a coarse (pebble-grade) unit overlying the already coarsening-up delta sequence (Figure 4.24). Given the relatively fine grain size of the prodelta sequence, the pebble-grade material is interpreted as too coarse for distributory channel deposition, and is consistent with fluvial incision. The recommencement of relative sea-level rise (as evidenced by the aggrading distal lobes) elevated the fluvial profile and created subaerial accommodation space sufficient to allow deposition and preservation of the fluvial fills A and B. It is noted that this scenario could equally have been influenced by a number of other factors which control grading of the fluvial profile, for instance river discharge and sediment load variation (Schumm, 1993).

In the Ninian delta, 3D seismic reveals progradational oblique clinoforms (Enclosure 25). Overlying this clinoform unit in the Ninian field is an aggradational 'topset' succession, characterised by relatively continuous, sub-horizontal seismic reflectors, comparable to the geometry of the distal fluvial fill A in the Lagniappe delta. Updip in the Ninian delta, this sequence is not observed in detail. Log data from the East Shetland Basin describes a broadly coarsening-up sequence which becomes more pronounced towards the top of the unit. 3D seismic data demonstrates the uppermost coarsening (up to pebble grade) to occur at the base of the 'topsets'. Both deltaic depositional systems are lobate (Figure 4.15) with relatively small distal lobes (5km radius). The preservation of successively lower 'topsets' is suggested on 2D in the East Shetland Basin (Enclosure 10, although this could be a compaction effect), and is described in the Lagnaipe delta. Both deltas are probably fluvial-dominated. The Lagniappe deltaic system described by Sydow & Roberts (1994) is thus considered a reasonable analogue to the Ninian delta.

Comparison of the deltas

The similarities between the well log and seismic expressions of the Lagniappe and Ninian deltas illustrates a possible analogue of the topmost Sele interval as observed on 3D seismic data in the block 3/3 area. The occurrence of pebble-grade material in fill A was considered by Sydow & Roberts to be require too high an energy regime for the distributory channel, given the relatively fine grain size of the prodelta sequence. The grain size distribution of the Ninian delta is greater, ranging from predominantly silty claystone
to fine sand in the pro-delta / delta-front, and coarsening up into fine to very coarse grade in the 'topsets'; this compares with the finer (medium grained) pro-delta / delta-front of the Lagniappe delta (compare Figure 4.24 & section 4.8.2). There is no biostratigraphic evidence for a fluvial fill in the Ninian delta. Sydow & Roberts clearly demonstrate the aggradational nature of the fluvial fill, and the merging of this facies with the distal clinoform sets. The Ninian 'topsets' are also aggradational, and could be interpreted on regional seismic data as coeval with distal lobe deposition (section 3.5.6).

No regressive surface of marine erosion was observed at the base of the Lagniappe delta. Sydow & Roberts define their sequence boundary as the surface of clear fluvial erosion overlying the progradational clinoform sets. Their decision was made despite not recognising an equivalent basinward surface, and despite the fact that in a distal position, the juxtaposition of fluvial and delta-front facies was not a significant basinward-shift in facies. They support their argument by demonstrating that proximally, on the mid-shelf, the surface of fluvial erosion superposed fluvial and pro-delta facies and, more importantly, it was unambiguous on both seismic and well log data. Thus the system described by Sydow & Roberts (1994) is chronostratigraphically represented as in Figure 4.25a. This system is analogous to the Ninian delta in having no erosive base.

Sydow & Roberts consider the local flooding of lobes (e.g. the 3.2 to 3.1 transition in their well; Figure 4.24) to be at least partly due to dewatering and compaction in the delta-front, which locally overcame sea-level variations (dewatering and compaction occurred at up to 10mm / year in the Lafourche lobe of the Mississippi; Nummedal, 1983). Thus they consider that both relative sea-level rise and fall can coexist locally. This would also be an explanation of the observed aggradational delta 'topsets' and progradational distal lobes in the Ninian delta, if they were coeval.

The scale of the updip erosion and observed channelling in the two deltas differs significantly. No channel features were observed in the Ninian delta (the minimum vertical resolution in the Ninian 3D data is in the order of 40'). In terms of the updip erosion, Kindinger (1988) describes fluvial fill A as having removing most of the deltaic sediments on the mid-shelf (Figure 4.23). Although clear erosion is observed in the Bressay area, the lateral extent of this appears to be limited, and any erosion updip from Bressay is outside the dataset. However, as noted by Dixon & Pearce (in press), further south, west of the Beryl Embayment, very large erosional canyons are observed. In contrast to the above
SB = Sequence Boundary, FRWST = Forced Regression Wedge Systems Tract, HST = Highstand Systems Tract, LPWST = Lowstand Prograding Wedge Systems Tract

Figure 4.25. Alternative chronostratigraphic interpretations for deltas which have undergone forced regression (adapted from Hunt & Tucker, 1992). See text for discussion.
examples, Suter et al. (1987) describe (non-glacio-eustatic) Holocene progradation of the Mississippi, which lacked subaerial exposure and fluvial erosion.

The chronostratigraphic implications of the above alternatives are illustrated in Figure 4.25. In Figure 4.25a, the delta 'topsets' (red in Figure 4.25) are a discrete sequence, separated from the underlying clinoforms (in orange) by a sequence boundary (SB, blue). The 'topset' sands would therefore be delta plain sands (section 4.10.2). This is equivalent to scenario c) in section 4.10.5 and Figure 3.18c.

Alternatively, the 'topsets' and clinoforms could be considered to be genetically related (Figure 4.25b). This interpretation corresponds to scenarios a) or b) in section 4.10.5, the interpretation of the topsets as being transgressive (section 4.10.4), and Figure 3.18b. In the second interpretation (Figure 4.25b) a regressive surface of marine erosion marks the base of the sequence, as described by Posamentier et al. (1992). As noted previously, these interpretations cannot be biostratigraphically differentiated in the case of the Ninian delta.

4.13 Summary of the Ninian delta

The available data cannot resolve the nuances of the complex Ninian depositional system, but the 'topsets' of the Ninian delta are interpreted in this thesis to be fluvial (delta plain) in origin, as supported by the following observations:

a) The common description of rounded pebbles in cuttings suggests high energy fluvial or near-shore (beach?) depositional environments.

b) The occurrence of sub-rounded pebbles up to 4cm long in core, implies that transgression of the shoreline had took place, i.e. that the underlying sequence was updip of the shoreface.

c) Log profiles indicate a coarsening-up succession of sands, but in the block 3/3 area, these are consistently interbedded with sharply-defined claystones (section 4.8.3), implying rapid lateral facies changes, possibly overbank deposits.

d) The interpretation of the 'topset' sands becoming discontinuous updip of the most distal lobes (section 3.5.6) suggests a possible link between the two. Comparison
with the hi-resolution studies shows fluvial fills supplying distal lobes (Sydow & Roberts, 1994). Other similarities between the Lagnaipe delta and the Ninian delta presents circumstantial evidence of fluvial topsets.

In blocks 3/1 through to 3/3 in the centre of the delta, the upper boundary of the 'topsets' is very abrupt on sonic logs. This data, together with the sharp change to offshore facies observed in core suggests that there was some (unquantified) erosion at this boundary, decreasing both up and down dip from block 3/2. The fact that this transgression was preceded by more argillaceous deposition in places (i.e. the widespread shales interpreted from logs) may imply that accommodation space was already increasing before the 'topset' sands were fully transgressed.

The clear evidence of incision, and the sub-spherical pebbles in cuttings in the Bressay area (block 3/28) also indicate fluvial activity updip (see chapter 5). Significant erosion is observed on the East Shetland Platform in the Quad 9 area, but no erosion was observed in this dataset directly updip from the Ninian delta. This concurs with regional mapping by others (R. Anderton, pers. comm.). No incision was observed on delta in the East Shetland Basin itself. These data together imply that the delta was fed from the southwest, and that fluvial entrenchment only occurred south and west of the East Shetland Basin. This is consistent with the observation of incision in the East Shetland Basin in block 9/8 by Milton & Dyce (in press).

The delta 'topsets' are unlikely to be a shoal water delta deposit, as coarser sediments would be expected to be less dominant in Ninian (given the calibre of the underlying cliniforms) and a shoal water delta would have fines underlying it and distally (e.g. Boyd et. al., 1989). The interpretation of the 'topsets' as an aggrading, transgressive offshore sand body is possible, but with the increasingly coarse grained sediment load, the sharply defined 'topset' claystones cannot be accounted for.

Identifying the number of sequences in the Ninian delta is beyond the resolution of the data. The driving mechanisms for the observed changes are thus unknown. High-resolution studies of the equivalent onshore successions suggest that there were only two significant relative sea-level fluctuations during this period (Powell et al., 1994; Neal et al., 1994). Sediment supply changes though the Paleocene, which were obviously very significant, thus may have encouraged autocyclic avulsion. Certainly, evidence from high
resolution studies have shown autocyclicity can exceed the frequency of eustatic sea-level fluctuations (e.g. Morton & Price, 1987), and the resulting lobes produce similar sequences (e.g. Suter et al., 1987). Lastly, it is of note that if ancient cycles are not formed by glacial-eustatic mechanisms (see Frakes, 1979) then there is no other process capable of producing rapid, globally-synchronous changes in sea-level (Donovan & Jones, 1979).

4.14 Limits of interpretation

The database used for this study in the Ninian area included 23 wells and good quality 3D seismic data, but no biostratigraphic data, and little core coverage. Despite this high resolution database (in subsurface terms) the interpretation of the Paleocene section was not well constrained, in terms of assessing the delta evolution, and the lateral correlation of the 'topsets' in particular.

The 'topsets' have been defined by previous authors (the Dornoch Formation of Mudge & Copestake 1992b; the topsets of Den Hartog Jager et al., 1993), but detailed 3D seismic mapping of the boundary between the 'topsets' and the underlying clinoforms demonstrated that they did not have a consistent well log character (Enclosures 22 & 23, Figure 4.8): where the 'topsets' overlay a sand-prone delta front succession, there was no change in lithology across the boundary. Correlation of this unit outside the area of the 3D seismic survey was uncertain.

This situation is not improved with the use of sequence stratigraphic over lithostratigraphic correlations. The detailed work carried out here demonstrates that, in the absence of core, the boundary can only be identified on 3D seismic data. As a consequence, the interpretation of the 'topset' depositional environments is ambiguous. Thus it is not possible to confidently assess from the data whether base-level was rising (a transgressive interval; section 4.10.4) or falling (regressive; sections 4.10.2 or 4.10.3) during the deposition of the topmost sands.

4.15 Conclusions

The observations in this chapter of the Maureen and Andrew / Lower Balmoral sequences are consistent with their interpretation as marking the change from relatively quiet marine sedimentation (Maureen sequence) to very significant clastic supply to the margins of the
East Shetland Basin. Slope bypass is interpreted over the underlying Jurassic structures, and is consistent with turbidity current deposition, as demonstrated in block 211/29 (section 3.5.4).

The Ninian delta was defined in the Ninian field area. Detailed mapping of 3D seismic data and a high density well database demonstrates that the Forties / Sele sequence in the area is represented by prograding deep water delta. Clinoform delta progradation is observed to be lobate. No evidence of significant base-level changes are observed associated with lobe switching.

The abandonment of the delta lobes is interpreted as having a significant influence on the development of younger lobes in the same area. The changing depositional profile of the abandoned lobe is likely to have influenced accommodation space, and the shape of the depositional profiles probably encouraged the development of clinoforms away from the previous depocentre. This was due to both the shallower depositional gradient, and the fact that a shallower slope dissipates any wave power (and hence reworking potential) more effectively. The reverse is true of depositional profiles close to the previous depocentre: steeper profiles gave rise to mass flow processes, and did not dissipate basin wave energy as effectively.

A number of alternative interpretations can explain the observed thick 'topset' succession of the delta. The delta top sands are suggested to be the deposits of avulsing delta-plain bedload channels, or possibly delta-front deposits. This interpretation explains the well log profile in block 3/3 which indicates a coarsening-up sand sequence becoming interbedded with well defined, high-gamma (overbank) shales. The limited core data from well 3/3-11 indicates a relatively rapid transgression of the delta top (probably by in-place drowning). However, interpretation of the succession is ambiguous, even with this very high resolution subsurface database.
Chapter 5

The Bressay Area

5.1 Introduction

This chapter describes the evolution of the Paleocene sedimentary distribution systems in the Greater Bressay area, UKCS blocks 3/27, 3/28, 9/2, 9/3, 9/7 and 9/8 (Figure 5.1). The comprehensive dataset comprised log data from all wells in the area, biostratigraphy from most of these wells and a closely spaced grid of regional and block-specific seismic lines. The objectives of the work were to detail the sediment pathways in the Greater Bressay area and contrast this with coeval sedimentation downdip in the Beryl Embayment, Viking Graben and Alwyn Slope. Chapter 6 reviews this information in the broader evolution of the Northern North Sea.

Following an introduction to the structural setting of the area, this chapter describes the database used. The results are then described and the depositional evolution of each sequence is discussed. The prospectivity of the Paleocene on the East Shetland Platform is briefly considered at the end of the chapter.

The available data varied considerably in quality and thus the level of detail altered across the study area. The terms used to differentiate these areas (see Figure 5.1) include the Greater Bressay area referring to the Alwyn Slope, Viking Graben and the Beryl Embayment juxtaposed to the Bressay area. The Bressay area comprises blocks 3/27, 3/28, 9/2, 9/3, 9/7 and 9/8 forming the promontory of East Shetland Platform. The 9/3 discovery is the north-south trending ridge at top Sele level in block 9/3a. The Bressay discovery is the southwest-northeast trending ridge at top
Figure 5.1. Structural context of the Bressay High to the southwest of the East Shetland Basin. Inset shows well data and block boundaries.
Sele level in SW block 3/28 & SE block 3/27. **Blocks 3/27, 3/28 south** is the area of these blocks covering the East Shetland Platform as opposed to the Alwyn Slope.

### 5.2 Structural Setting of the Greater Bressay area

A range of post-rift geometries resulted from the failed Jurassic rifting in the North Sea. In the Viking Graben, rifting occurred early and was concentrated over a narrow area (Underhill & Partington, 1994; =60km at 60°N), resulting in sharp bathymetric relief across a relatively short distance. In contrast, brittle extension in the East Shetland Basin area took place across a distance of approximately 150km at 61°N, spread across a complex system of half-grabens. The structural style was also complicated by the Bressay granite, which formed a protuberance on the west side of the Viking Graben (Condon, 1988).

The Beryl Embayment formed a Late Jurassic terrace on the western margin of the Viking Graben and is separated from the Bressay area by a single fault. This structural style contrasts with the northern Bressay margin (Figure 5.2) where the Alwyn slope forms a transfer zone between the major basin bounding faults. Late Jurassic and Cretaceous subsidence outstripped sedimentation which combined with differential compaction, maintained the relief of the Jurassic structural elements. The resulting structural style around Bressay controlled Paleocene sediment distribution.

Well data indicate a thin Mesozoic succession preserved subjacent to the Paleocene in the Bressay area, overlying Devonian (Old Red Sandstone) sediments. On the grounds of gravity and magnetic modelling, Holloway *et al.* (1991) considered these sediments to mark the edge of a Devonian basin west of the Bressay granite (Figure 5.3).

### 5.3 Previous Work

Previous work in the Greater Bressay area and the Beryl Embayment comprises purely stratigraphic work (Dixon & Pearce, *in press*; Dixon *et al.*, *in press*; and Milton & Dyce, *in press*; Mudge & Copestake, 1992b; Timbrell, 1993) and work which has also considered the structural controls on sediment deposition from a regional perspective (Condon, 1988; Morton, 1982; Morton *et al.*, 1993; Mudge & Bliss, 1983).

Morton *et al.* (1993) studied the evolution of sand provenance between 59 and 60°N in the Northern North Sea. They discerned three provenance areas for the sub-Sele
Figure 5.2. Base Cretaceous structure map of the Bressay area highlighting the contrasting structure of the Alwyn Slope and the Beryl Embayment (after Holloway et al., 1991). The East Shetland Platform is stippled. Note that the 1500ms contour shows that the dip of the East Shetland Platform is approximately perpendicular to graben boundary, with the exception of the southern Bressay area.
Figure 5.3. a) Observed gravity and magnetic anomalies over the Bressay High (after Holloway et al., 1991). Contour values in milligals and nanotesla respectively. b) Modelled prisms of Holloway et al. (1991). Stippled block 'G' represents the modelled granite.
**BP SEQUENCE STRATIGRAPHIC FRAMEWORK IN QUAD 9**

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Figure 5.4. BP sequence stratigraphic framework in the Quad 9 area (from Dixon et al., *in press* and Dixon & Pearce, *in press*). The BP sequences are defined by gamma maxima and constrained by a detailed biostratigraphic framework (see Dixon et al.). Cross-hatching indicates condensed sections (Graphic Correlation terraces) in the stratigraphic scheme used in this thesis. See also Enclosure 3.
sequence Paleocene sands on the basis of mineralogical differences. On the East Shetland Platform, they described a complex history of sand deposition in the early Paleocene (Maureen to Lower Balmoral sequences of this work) which cannot be supported or disproven by this work. In the basin however, they described a series of mineralogical units (MT1 to MT6) which biostratigraphic data shows to conform to the sequences described herein (Enclosure 3). The provenances described by Morton et al. (1993) indicate that in the Andrew / Lower Balmoral sequences there was a shift in deposition to the north of the East Shetland Basin, as described by Heritier et al. (1979) and Morton (1982) and in chapter 3. Mudge & Bliss (1983) in contrast separated the sand-prone Andrew / Lower Balmoral sequences quite differently (Figure 1.13). Morton et al. (1993) attribute the observed Andrew / Lower Balmoral sands as indicating fault reactivation (following Morton, 1982). However, Condon (1988) and Bertram & Milton (1989) considered that there was no evidence to support active extension or faulting in the Paleocene (section 6.5).

Dixon & Pearce (in press), Dixon et al. (in press) and Milton & Dyce (in press) described the sediment distribution in the Quad 9 area in detail, work which this study extends to the north. As described in section 1.4, the BP sequence stratigraphic approach varies from that of other authors in defining the sequence boundaries on gamma maxima (Figure 5.4; Enclosure 3), a method which is followed here where appropriate. Dixon & Pearce described progradation on the shelf during the Forties interval, followed by widespread incision updip of the Beryl Embayment in the Sele sequence (their sequences T46 & T48). They described further significant incision in the Bressay area (Figure 5.5). This Sele incision is equivalent to that described in this chapter, and indicates that the regional significance of work described here. This study extends the BP work, showing that the incision is more complex than a single event.

In the Beryl Embayment itself, Milton & Dyce described a 3D dataset covering blocks 9/8a and 9/9, in the southeast of the study area (Figure 5.1). They again observed base-level fall in the Sele sequence (their T46 interval), which in the 3D survey dissected and isolated coastal systems as base-level continued to drop (Figure 5.6). These deltaic remnants were termed Midstand Systems Tracts by Milton & Dyce, defined on their upper and lower boundaries by erosive unconformities, and caused by a small relative sea-level fluctuation during a more significant regional base level fall. Milton & Dyce describe midstand delta sequences in the Beryl Embayment as post-dating the deltaic sequences in the Bressay area, and pre-dating the younger (T48) stratigraphy downdip.
Figure 5.5. T46 (left hand side) & T48 gross depositional environments from Dixon & Pearce (in press). The maps show the paleogeography of the lower and upper Sele sequence respectively. They demonstrate the regional extent of the fluvial systems into the East Shetland Platform. However, they are very generalised (R. Dixon, pers. comm.), and the incision in the 9/3 area is shown in this study to drain to the north. See Figures 5.4 and Enclosure 3 for correlation with this work.
Figure 5.6. Geological map of the blocks 9/8 and 9/9 areas for the Sele / Balder sequences (from Milton & Dyce, in press).
5.4 Database

Wireline logging suites (in most cases composite, dipmeter and density-neutron logs) were used for this chapter from the following wells:

- 3/27-1 (1Z)
- 3/27-2
- 3/28-1
- 3/28a-2 (TD in Sele sequence)
- 3/28b-3
- 9/2-1 (A)
- 9/3-1
- 9/3-2A
- 9/3-3
- 9/3-4
- 9/7-1

Wireline log data were also used from the surrounding blocks (Figure 5.1). Of 1550km of seismic data available, 730km was interpreted interactively using GeoQuest software. The 730km of digital data was the most densely spaced data (Figure 5.7). The seismic surveys used were as follows:

<table>
<thead>
<tr>
<th>Survey</th>
<th>Data provided by</th>
<th>Form</th>
<th>Line kms</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMO/sov-812</td>
<td>Chevron, Sovereign,</td>
<td>digital</td>
<td>730</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>total</td>
</tr>
<tr>
<td>UK85</td>
<td>Enterprise</td>
<td>digital</td>
<td></td>
</tr>
<tr>
<td>C-L9/81, C9/84</td>
<td>Conoco, Conoco, Chevron</td>
<td>paper</td>
<td>820</td>
</tr>
<tr>
<td>(various regional)</td>
<td></td>
<td>paper</td>
<td>total</td>
</tr>
</tbody>
</table>

The biostratigraphic data was of variable quality. Good biostratigraphic data was available for the wells 9/3-1 and 3/28b-3, but in wells 3/27-1, 3/28a-2, 9/2-1 and 9/3-2A, quality was not good enough to independently define sequences in the wells.

5.5 Stratigraphy

5.5.1 Seismic stratigraphy

Wells 3/27-1, 3/28-1 and 3/28a-2 penetrate a significant linear feature running SW-NE through the south of the block. However, lateral changes in differential compaction and velocity data imply that the stratigraphy in these wells is unrepresentative. Combined with the poor biostratigraphic data in these wells, correlation of the Paleocene in the area relied heavily on seismic mapping to establish the distribution of the sequences.
3/28: 730km digital data interpreted on workstation

N Viking Graben

Figures 4.18, 4.19

9/4-1
9/4A-2a

Graben boundary

Figure 5.7. Seismic database used over the Bressay area. For wells see Figure 5.1.
Figure 5.7b. Location of seismic figures used in this chapter.
The variable data qualities of the seismic, well log and biostratigraphic data resulted in quite different resolution across the Bressay area. The following descriptions are representative of the areas of highest data quality in each area. Enclosures 26 and 27 summarise the seismic characteristics of the sequences in the Greater Bressay area.

Well logs were tied to seismic using velocity data only - no synthetic seismic sections were available. The seismic to well ties at the top Balder and base Paleocene level were most confident, and the ties were generally good. However, the very significant lateral changes in velocity meant that for instance on line LMO-812-37, the tie was poor. However, the error was as expected: as the seismic waves sample proportionally more of the slower lateral stratigraphy than the well, the seismic picks were lower than observed in well 3/27-1. The minimum resolution of the seismic was approximately 45 feet (1/4 wavelength; dominant frequency = 45Hz; velocity = 8000 feet per second).

5.5.1.1  **Andrew and Upper Balmoral sequences**

In the Bressay area, the Andrew sequence has a similar seismic character to that of the Upper Balmoral sequence, and the two units were mapped together (Enclosure 26). The sequences are relatively transparent, and have low to moderate reflector continuity; there is no distinguishable internal boundary between the sequences. The isochron of the combined sequences shows a thinning trend towards the south of blocks 3/27 and 3/28 (i.e. towards the north; Figure 5.8), from greater than 200ms to less than 50ms. Beyond the edge of the Bressay area, where biostratigraphic control allows the sequences to be separated (Figure 5.9), both sequences thicken abruptly away from the platform. (Figure 5.11). The Andrew sequence onlaps against the platform at a structurally low level (Enclosure 28). The Upper Balmoral sequence progressively onlaps the Andrew sequence and the East Shetland Platform, while distally downlapping the Andrew sequence (Enclosures 27 and 28).

5.5.1.2  **Forties and Sele sequences - southern 3/28 area**

* Mounding in the Sele sequence

As described in section 5.5.2, the Forties and Sele sequences could only be differentiated over a limited area. Outside this area, the Forties and Sele sequences together have a sheet-like external form, with the exception of elongate areas of thickening (Figure 5.10). This is the reflection of both mounding on the upper surface,
Figure 5.8. Upper Balmoral to base Paleocene isochron (TWT)
Figure 5.9. Graphic Correlation of well 3/28b-3 on the Alwyn slope. Vertical axis is composite standard units (CSUs). Gamma log to scale.
Figure 5.10. Forties / Sele / Balder isochron for the Bressay field. The significant changes in thickness of this interval are due to both differential compaction over the sand-rich Forties and Sele sequences, and incision at the base of the interval. The two areas of thickening represent in the north, the shelf-perched delta on the Alwyn Slope (Figure uk112) and in the south, the incision and compaction of the Forties and Sele systems. Notice that there are two thickening trends in the south of the area: the linear feature corresponding with the incision at the base of the interval (Figure UB-bPc); and the more north-south trend observed immediately updip of the 100ms contour. This latter trend is associated with the offlap break of the clinofoms observed in this area (Figure uk103). See text for discussion. Isochron thickness range 70 to 260ms. Units on scale bar 2kms. See Enclosures 32 & 33 for block boundaries and field locations.
and incision at the base of the unit. Within the mounded areas, the Forties / Sele interval displays varied seismic geometries (Enclosure 26); onlap (Figure 5.12), downlap (Figure 5.13) and bidirectional downlap (Figure 5.14). Seismic reflectivities of the mounds tend to be high, with occasional very high amplitudes are observed (Figure 5.14). The thickness of the isochron reaches almost 260ms (>1000') north and east of well 3/28-1 (Figure 5.11).

The mounding of the Sele interval as expressed by the top Balder map (Figure 5.15) shows a lateral change in depth of c. 70ms (c.300') which is inferred to be largely due to differential compaction. Simply projecting the base of the mapped incision from the seismic directly onto the position of well 3/28-1 gives an estimated incision of 170' (Figure 5.14). Flattening the section & repeating this gives estimated incision of 280' (Figure 5.16). There is a striking similarity between the areas of greatest differential compaction and the 'mounding' of base Paleocene reflector. The strength of the correlation is such that it is inferred that the basal Paleocene 'mounding' is an artifact of pull-up by an overlying sand-rich interval. This is supported by the change in reflector character and amplitude in the Sele above the base Paleocene 'mounding'.

The compaction over the mounding implies that the post-Upper Balmoral sequence underwent very significant differential compaction. Modelling was undertaken to try and estimate the lateral change in sand content of the post-Upper Balmoral section, given that the amount of pull-up could constrain the lateral changes in bulk velocity across the post-Upper Balmoral Paleocene interval (section 5.8.4).

**External to mounding**

Outside the mounded areas, the Forties / Sele interval has moderate to high reflectivity, and generally downlaps onto the underlying Upper Balmoral sequence (Figure 5.12). Internally the interval displays bidirectional downlap. The Forties / Sele interval thins to the west of the survey area, but thickens to the east, where the Forties and Sele interval can be separated (well 3/28b-3, Enclosure 9). In these areas, the Forties interval displays moderate to high amplitude reflectors which downlap to the east, and continue to the margin of the Viking Graben (Enclosure 28). The Sele interval also downlaps to the east, displaying downlap (clinoform) geometries, but the depositional limit of offlap does not reach the margin of the platform in block 3/28 (Enclosure 28). The clinoform geometries are along strike from the high in block 9/3 (Enclosure 9).
Figure 5.11. Upper Balmoral to base Paleocene isochron for the Bressay field. This diagram represents the thickness in time of the Lower and Upper Balmoral sequences in the area of the Bressay field. The very significant thinning of the interval in the south is predominantly due to incision by the overlying Forties sequence. The incision is observed to increase to the East: the right hand edge of the figure coincides with the margin of the North Viking Graben, where slope bypass occurred. To the west, the incision becomes confined to two narrow zones running west and southwest. These correspond to the 'K' prospect and the Bressay field respectively. See text for discussion. Isochron thickness range 42 to 397ms. Units on scale bar 2kms. See Enclosures 32 & 33 for block boundaries and field locations.
Figure 5.12. Seismic line Sov-812-22 showing reflector onlap against the margins of the incision (top Upper Balmoral; dark green). Note that differential compaction of the incised area has led to distinct mounding of the Top Balder (black) and Top Sele (dark blue) surfaces. The base Paleocene reflector (lighter green) shows some limited pullup, and a distinct decrease in continuity under the incisioned area. The lack of reflector integrity probably results from the rapid lateral velocity changes. Horizontal lines are 100ms apart. Width of displayed section c.5km.
Figure 5.13. Seismic line Sov-812-29A illustrating downlap inside the mound, both against the margin of the incision, and further up in the composite body. Horizons: Base incision = top Upper Balmoral = dark green; Top Balder = black; Top Sele = dark blue; base Paleocene = lighter green. Horizontal lines are 100ms apart. Width of displayed section c.5km.
Figure 5.14. Seismic line SOV-812-27 demonstrating bidirectional downlap onto either edge of the incision. Note that the mounding due to differential compaction of the top Sele surface occurs across a greater area than the area of pull-up. Horizons: Base incision = top Upper Balmoral = dark green; Top Balder = black; Top Sele = dark blue; base Paleocene = lighter green. Horizontal lines are 100ms apart. Width of displayed section 5km. See Figure 5.7b for location.
Figure 5.15. The top Balder time-depth map in the Bressay area. Note that in the southwest of the area, very prominent mounding (and closure) occurs in two areas. The two areas have a elongate form in the southwest, and a more circular form in the centre-west. Colour as in other depth maps runs from red (shallowest) to blue (deepest).

For block boundaries and field location, see Enclosure 32.
Figure 5.16. Seismic line Sov-812-27 flattened on the base Paleocene reflector. This section does NOT approximate to a paleogeographic reconstruction, but does emphasise the depth of incision. Projection of the edge of incision onto well 3/28-1 gives an estimate of incision of 280'; undertaking the same exercise on the unflattened seismic line gives an estimated incision of 170'.

Horizons: Base incision = top Upper Balmoral = dark green; Top Balder = black; Top Sele = dark blue; base Paleocene = lighter green. Horizontal lines are 100ms apart. Width of displayed section c.5km.
5.5.1.3 Forties and Sele sequences - 9/3 area

In the 9/3 discovery, the Sele and Forties intervals can again be tentatively differentiated (Figure 5.17). Clear bidirectional downlap occurs in the Forties interval in the western half of the 9/3 discovery, and at the base along the length of the interval. An irregular upper surface to the Forties sequence hinders the interpretation of the Forties / Sele contact, and two interpretations are suggested: a base Sele pick subhorizontal to the Forties interval, showing no significant erosion into the subjacent strata; and a base Sele pick draping the underlying mounded Forties topography.

To the west of the 9/3 discovery, the Sele sequence incises down into the Forties section, preserving an irregular, sinusoidal boundary. The combination of mounding in the Forties / Sele interval and irregular incision at the base of the interval complicates interpretation, and the two units cannot be confidently differentiated on paper seismic sections as the combined interval thins to the west (Enclosure 7). Incision at the base of the Sele interval appears to increase westwards (updip) between 9/2-1 and 9/3.

No clear erosion is observed on seismic data. The Sele sequence does not continue east of the block 9/3 high, suggesting that as in block 3/28, the Sele offlap break on the platform occurs short of the graben margin.

5.5.1.4 Forties and Sele sequences - northern 3/28 area

On the Alwyn Slope, the Forties interval is relatively thin, although mapping demonstrates a slight thickening at the very edge of the platform (Enclosure 28). Reflectors predominantly downlap; reflectivity and continuity decrease at the edge of the shelf. The overlying Sele sequence is lensoid in cross-section, c.3.5km wide, and elongate in a strike direction (Figure 5.11). Sele reflectors display basal downlap, and no obvious upward termination.

5.5.1.5 Balder Sequence

The Balder sequence is a relatively thin interval, but has a strong seismic signature. The strength of the wavelet largely obscures the internal seismic character. The key seismic characteristics of the Balder sequence are summarised in Enclosure 26 and 27. The sequence clearly onlaps against the Forties / Sele highs, in both a basinward and marginward direction.
Figure 5.17. Detail of a seismic line over the 9/3 prospect showing the offlap break of the Sele seismic sequence to the east, and incision into the underlying Forties seismic sequence to the west. Note the bidirectional downlap of the Forties seismic sequence onto the underlying Upper Balmoral seismic sequence; evidence of incision at this surface is unclear. See Figure 5.7b for location.
5.5.2 Biostratigraphy

The biostratigraphic framework used here was constructed for the Northern North Sea using the graphic correlation method (section 2.7). The result of this work was the definition of a high-resolution stratigraphic framework (section 3.4), which was used along with well log data (gamma, resistivity, sonic, dip-meter and density-neutron logs) to the subdivide the stratigraphies in wells 9/3-1 and 3/28b-3. The limited biostratigraphy in other wells (3/27-1, 3/28A-2, 9/2-1 and 9/3-2A) also allowed some sequences to be defined in these wells.

No fauna older than Gavelinella beccariiformis were recorded in any of the East Shetland Platform wells, suggesting that the Maureen, Andrew and lowermost Lower Balmoral sequences were missing (Figure 5.18). The Upper Balmoral sequence was interpreted in all the wells, but the identification of the overlying Forties and Sele sequences was less clear. The Forties and Sele sequences could be differentiated in wells 9/3-1, 9/3-2A and 3/28b-3, but identification was uncertain in the rest. Although sampling was relatively good in the Forties and Sele sequences in well 9/3-1 (and in the uppermost Sele sequence in 3/28A-2), biostratigraphic resolution was not high enough to discern whether the sediments were of early or late Sele sequence ages.

5.5.3 Log descriptions

(Andrew) Lower Balmoral sequence

The base of the (Andrew) Lower Balmoral sequence is represented by a sharp break with the underlying Mesozoic strata on all well logs. In the south of blocks 3/27 and 3/28, the (Andrew) Lower Balmoral sequence comprises light to medium grey, grey-green to brown, silty claystones (sub-fissile to blocky). The sediments are micaceous and carbonaceous, and occasionally glauconitic, pyritic or calcareous. The interval is similar in blocks 9/2 and 9/3, where they comprise light to medium grey-brown, blocky, micromicaceous siltstones, with echinoid spines. The sequence thins from around 350 feet in 9/2-1 to less than 250 feet in well 3/28-1 (Enclosures 8 and 29).

In contrast, the (Andrew) Lower Balmoral sequence in well 3/27-2 is thicker (560'), and dominated by clear to opaque fine to coarse grained sand, with occasional light grey, well rounded pebbles. The sand is poorly sorted, subangular to well rounded, unconsolidated and pyritic and is intercalated with micaceous claystones and siltstones.
Figure 5.18. Wells 9/3-1 and 3/28b-3 CSU-depth plots compared to the Northern North Sea framework. Note that deposition does not start in either well until after the start of the Lower Balmoral sequence.
Microconglomeratic bands occur towards the base. Limestones and dolomites commonly towards the base of the sequence. A short core was recovered from well 3/27-2 but this was just a box of unconsolidated sands in the DTI coreshed. The sands were fine to coarse grained, moderately to poorly sorted sand, commonly with polymodal (very fine to fine; medium to coarse; coarse to granule) modes. A summary core description chart described mudclasts, micas and plant fragments locally concentrated at the tops of the beds, which were described as mostly massive, normally graded, and with locally with discernible dish structures. Burrowing and bioturbation also occurred towards the tops of beds.

Interpretation is difficult based on these descriptions alone, but the massive beds; the normal grading confined to the uppermost parts of beds; and the restriction of fines, micas and plant fragments to the tops of beds would conform to an interpretation of deposition by turbiditic processes.

**Upper Balmoral sequence**

Like the (Andrew) Lower Balmoral sequence below, the Upper Balmoral sequence is dominated by claystones, with cuttings descriptions very similar to the (Andrew) Lower Balmoral sequence. Similar thickness variations also occur, from about 250 feet in 9/2-1 to less than 100 feet in well 3/28-1, thickening again in 3/27-2 (150'). However, interbedded sands occur, which are light grey to clear, fine to very coarse, physically immature (subrounded to subangular, very poorly sorted), and occasionally pebbly. The sands are generally unconsolidated, with traces of glauconite and lignite. A distal shelf depositional environment is suggested.

A break in the density-neutron and dip-meter logs occurs at the base of the Upper Balmoral sequence. The gamma and sonic logs converge at the boundary, followed by a drop in the gamma values uphole; this gamma high is seen at the top of the sand in well 3/27-2. In the absence of biostratigraphic data, well log character was used to correlate the sequence across the Greater Bressay area.

**Forties and Sele sequences**

In the south of blocks 3/27 and 3/28, the Sele sequence is a thick, sand-rich interval (823', with a sand to shale ratio of 8:1 in well 3/28-1) interpreted as incising into the underlying Forties and Upper Balmoral sequences. The interval consists of off-white
to grey, loose to unconsolidated sands (very fine to very coarse grained; moderately sorted to unsorted; coarse grained to granular; pebbly). Grain roundness varies from subangular to subrounded. Pebbles are described as subrounded to rounded, sub-spherical, of quartz and clay composition, and occur throughout the section. Interbedded silts are light to medium grey, grey-brown, sandy and micaceous, to very micaceous, locally carbonaceous, with interlaminated sands. Sele sands in the 9/3 area are similar, rarely interbedded with abundantly pyritic claystones. The Sele interval thins towards 9/2-1 (330') and 3/27-2 (270'), although cuttings descriptions remain similar. Coarsening-up cycles are described in the Sele interval of well 9/3-4.

Differentiation of the Forties and Sele sequences on cuttings descriptions alone is subjective, but there is a tendency for the Forties sands to be slightly finer (fine to medium; medium to very coarse) and slightly better sorted. Descriptions of the Forties sequence notably lack pebbles. The sequence is more sand-rich than the Sele sequence in block 9/3. Fining-up cycles are described in the Forties (?and Sele) sequence of well 9/3-3. The Forties sequence becomes argillaceous towards well 9/2-1 and well 3/27-2.

In block 9/3 the base of the Forties / Sele sequence is defined by clear a gamma and sonic break at the base of the sand. In well 9/2-1, a clear change in the density-neutron and dip-meter logs is observed. The base of the Sele sequence in block 9/3 is defined biostratigraphically in well 9/3-1 (Enclosure 6) and marked on well logs by a sharp drop in the sand to shale ratio. The converse is true in wells 3/27-2 and 9/2-1 where the change from the Forties to the Sele sequence is marked by abrupt increase in sand.

Immediately north of the Bressay area, biostratigraphic data from 3/28b-3 allows the Sele and Forties sequences to be differentiated (Figure 5.9). The Forties interval in 3/28b-3 is 250 feet thick and the Sele interval is approximately 400 feet; both display heterogeneous, broadly cleaning-up log profiles. The only available biostratigraphic water depth estimates indicate a shallowing from bathyal to bathyal / outer sublittoral in the Forties sequence, which continues into the Sele sequence before deepening again.

**Balder Sequence**

The basal Balder sequence comprises medium to dark grey, very silty, blocky tuffaceous siltstones, with occasional glauconite, calcareous concretions and carbonaceous fragments. Thicknesses are reasonably constant, up to 180 feet. The sequence has a 'bowed' gamma-sonic profile, indicating the waxing and waning of the
tuffaceous content. The base and top of the sequence are defined on the upper and lower strong gamma-sonic bows, in common with other authors (e.g. Mudge & Copestake, 1992b).

5.6 **Evolution of the Lower / Upper Balmoral sequences**

5.6.1 **Observations**

The Lower and Upper Balmoral sequences are well defined in the Bressay area by biostratigraphic data from well 9/3-1 (Enclosure 6), and supporting biostratigraphic data in wells 9/3-2A, 9/2-1 and 3/27-1. The top of the Upper Balmoral sequence in well 9/3-1 is ambiguous: the top of the sequence could be picked higher (Enclosure 6; note that a log error occurs at 4250' which hinders interpretation). The sequence predominantly comprises silty claystones on the platform, and biostratigraphic information suggests deep water (bathyal) depths. The occurrence of echinoid spines may indicate continuing cannibalisation of Cretaceous strata updip. The occurrence of glauconite and pyrite indicates reducing conditions. Thus the sequences are interpreted as a low energy sediments that accumulated in a distal shelf setting.

In the Viking Graben and Alwyn Slope, the Andrew / Lower and Upper Balmoral sequences are predominantly arenaceous (Enclosures 12 and 8). Onlap of the Andrew, Lower and Upper Balmoral sequences is observed onto the Alwyn Slope (Enclosure 28), indicating that slope bypass occurred across the graben margin during deposition of the early Andrew sequence, as would be expected across such a steep break in slope. All the sequences thicken significantly against the graben margin (Enclosure 8), and the thickening shows little along-strike variation. Although the sampling density is not high in any of the wells save 9/3-1, it is significant that no biostratigraphic events were recorded older than *Gavelinella beccariiformis*. This, together with the absence of any observable log break at the top of the Andrew sequence in e.g. 9/3-1 and the upward transition of the Andrew sands into shales in the basin (Enclosure 6) suggests that deposition of the Andrew shales in the Bressay area may represent transgression of the platform following the major sand deposition in the basin. The implication of the facies change around 3/27-2 and 3/28b-3 (Enclosure 29) with respect to the wells immediately to the south is that the area around the north of blocks 3/27 and 3/28 acted as a sediment conduit with respect to the rest of the Greater Bressay area. The relative age of the two facies types cannot be constrained, and the sands in 3/28b-3 and 3/27-2 could correlate with either the basinal sands or the platform shales.
The base of the Andrew sequence is marked by a very strong reflector, due to the large acoustic impedance contrast with the underlying thin Cretaceous chalk. Although the dip of the base Paleocene surface is relatively even (Figure 5.19), strong mounds are observed, particularly in the south of block 3/28 (Figure 5.20). The change in the seismic character over the mounds; the contrast of the direction and form of the mounds with respect to the local base Paleocene slope; and the coincidence of the base Paleocene mounding with very significant differential compaction and incision in the Sele interval (section 5.8) all imply that the observed mounds are artefacts of velocity pull-up in the overlying Sele sequence (see section 5.8.4 for further discussion).

5.6.2 Conclusions

Early deposition of the Andrew / Lower Balmoral sequence took place in the Greater Bressay area, with sand by-passing the main Bressay area on the north and south. The absence of any reported taxa older than *G. beccariiformis* implies that the basal Paleocene non-deposition lasted until the late Andrew sequence in the area. It is interpreted that non-deposition occurred in the Bressay area (and by inference, the East Shetland Platform in the surrounding area) until the Lower Balmoral sequence, when it was subsequently transgressed. The Lower Balmoral sequence is observed to become shaley in the basin, which is probably coeval with transgression of the platform. The lack of along-strike variation in the thickness of the Andrew sequence against the platform margin suggests a fan apron depositional environment, probably with an axial component from the south. The ages of the Andrew / Lower Balmoral sands in wells 3/27-2 and 3/28-1 are not clear; these sand may imply that sands were still being fed to the basin after transgression of the East Shetland Platform. There is no evidence of incision at the base of the Lower Balmoral sequence. This accords with the estimated water depths (i.e. shallower than sublittoral water depths), and implies that non-deposition at the base of the sequence occurred in a sub-aqueous environment.

5.7 Evolution of the Forties sequence

5.7.1 Observations

Depositional environments

In block 9/3, the preserved Forties interval has a broadly cleaning-up log character, and tends to have a cleaner log profile than the overlying Sele sequence. Cuttings describe
Figure 5.19. Time-depth map of the base Paleocene (TWT)
Figure 5.20. The base Paleocene surface as mapped on seismic in the block 3/28 area. The W-E to SW-NE deviations from the main dip trends in the southern half of the diagram are due to pull-up of the surface by the sharp lateral changes in the sand content of the overlying unit. The units on scale bar at bottom of diagram are one kilometre.

For block boundaries and field location, see Enclosure 32.
fining-up cycles, and the common occurrence of glauconite and limestone bands. From this data, and the biostratigraphic evidence indicating some shallowing at the base of the sequence, it is inferred that the Forties sequence was deposited in shallow marine conditions. This is strongly supported by the evidence of erosion/incision in both the 9/3 and 3/28 area. Log profiles over the Forties sequence downdip (3/28b-3; block 9/8) also clean- (coarsen-) up, suggesting that Forties sequence was progradational.

Well and seismic mapping

Enclosure 29 shows the correlation of the Forties sequence across the Bressay area, and the lateral changes in depositional facies of the preserved sections. The subtle basal boundary to the Forties sequence in well 9/2-1 is seen to become gradually sharper moving from 9/2-1 to wells 9/3-4, 9/3-2A and 9/3-1. The facies change is therefore interpreted as being a depositional change, concomitant with (limited) incision of the Forties interval into the underlying Upper Balmoral sequence. This is consistent with the slightly shallower dip of the base Forties time-depth map in the 9/2 area with respect to the blocks 3/27 and 9/7 (Figure 5.21).

In the 3/28 area, very significant incision is observed at the base of the Forties / Sele interval. Figure 5.22 shows the basal surface of incision mapped out in the 3/28 area, and Figures 5.10 and 5.11 highlight the confluence of the two elongate thickened sand mounds ('canyons'). The isochron of the sub-Forties interval emphasises the broad erosion of the subjacent stratigraphy east of the confluence of the canyons, which continues to the edge of the platform margin. It is of note that the incision did not follow a course towards the Alwyn slope: it instead appears to have run parallel to the edge of it (c.f. Figure 5.21). The NW canyon is also very close to the Alwyn Slope, trending oblique to the base Paleocene dip.

In well 3/28b-3 on the Alwyn Slope, the Forties sequence is a relatively thin (c. 250') coarsening-up succession (Figure 5.9). The interval downlaps towards the platform margin on seismic (Enclosure 28). In the Viking Graben directly east of the Bressay area, a thick accumulation of Forties age sand occurs (350' boxcar sand in well 3/29-2; see section 3.5.5). This Forties sand body thins to the north and south (Enclosure 11). In block 9/8, the Forties interval is thicker than that observed in 3/28b-3, and thickens immediately away from the platform. The sands in this block 9/8 area are not contiguous with those in the 3/29 area (e.g. 9/4a-2A).
Figure 5.21. Top Upper Balmoral Time-Depth map (TWT)
Figure 5.22. The base of the Forties seismic sequence in the block 3/28 area. The deviations from the main dip trends in this diagram are due incision into the underlying Upper Balmoral sequence. The units on scale bar at the bottom of diagram are one kilometre.

For block boundaries and field location, see Enclosure 32.
5.7.2 **Conclusions**

The magnitude of the Forties incision (estimated from thickness of the sub-Forties section in 9/2-1) correlates approximately with a progressively more abrupt change to Forties sand deposition in block 9/3 (Enclosure 29). The lateral facies change of the Forties sequence on the platform is interpreted as being associated with the retrogradation of the higher energy facies into the underlying shales, as is predicted during forced regression (e.g. Plint, 1988). This can be deduced, even though the relationship of the preserved Forties succession to the surface of base Forties incision cannot be specified (the overlying sands may considerably post-date the incision). The identification of significant incision in block 3/28 implies that base-level dropped to (or below) the level of the platform.

In the 3/28 area, the incision developed further than in block 9/3. Seismic mapping demonstrates the existence of two canyons in 3/28, which converge and enlarge to the east, removing most of the subjacent Paleocene stratigraphy. The direction of drainage of the incised system, off the east of the Bressay area implies that the eroding fluvial systems followed a paleoslope dipping to the southeast. There is no evidence of pre-Forties incision in the area. The local development of a Forties sand body around block 3/29-2, and the absence of a continuous sediment pathway on the Alwyn Slope supports the interpretation of the canyon and valley system in block 3/28 acting as a conduit for the passage of Forties sediments out to the Viking Graben.

5.8 **Evolution of the Sele (Forties) sequence**

5.8.1 **Block 9/3 and surrounding area**

The similarity of the log profiles over the Sele sequence in block 9/3 allows the confident correlation of the interval between the four 9/3 wells. The wells are positioned approximately along strike, near the crest of a N-S high (section 5.5.3). The isochron of the combined Forties and Sele interval thins to the west of the 9/3 high, a trend which continues to the north (Enclosure 9). The isochron of the Forties-Sele interval is notably more cuspatate on the western edge of the 9/3 high, consistent with the observation of incision on the western flank of the high. This data, combined with the continued thickness of the 9/3 discovery into the north of block 9/8 (Enclosure 9), suggests that drainage took place off the 9/3 paleohigh to the west, and then downdip to the north through block 3/28. This hypothesis supports the interpretation of the base...
Sele in the 9/3 discovery as a relatively planar surface, with limited erosion (section 5.5.3). The Sele/Forties isochron maintains a thickness of greater than 150ms in block 9/7 (Enclosure 9), and no sign of incision is observed, although seismic data coverage is sparse in the area. This limits the catchment area of the new drainage patterns. The pattern is also consistent with the slope of the East Shetland Platform towards the graben margin in block 9/7.

The occurrence of the Sele offlap break short of the graben margin implies that Sele progradation in the 9/3 area pre-dated incision to the west. The direction of progradation is eastwards, approximately parallel to dip. It is inferred that continued base level fall changed the drainage patterns across the Bressay area, redirecting the sediment supply which had previously driven eastward progradation of the 9/3 high.

5.8.2 Block 3/28

The Forties / Sele sequence isochron in the south of block 3/28 indicate the preserved stratigraphy more than doubling in thickness in the mounded areas. Together with the pull-up of the base Paleocene reflector, the data imply very significant lateral changes in sand to shale ratio of the interval. As noted in section 5.5.1, wells 3/27-1, 3/28-1 and 3/28A-2 only penetrate the mounded areas and thus record a unrepresentative stratigraphy. Correlation of the Paleocene in the area therefore relies heavily on seismic mapping. In order to constrain the seismic interpretation, some simple velocity modelling was undertaken to simulate the observed pull-up and compaction features (section 5.8.4).

Seismic mapping

Seismic mapping of the basal Sele / Forties event demonstrates two erosional features in the west of the area (c. 2km wide) broadening out to the east into a significantly larger valley (c.5km wide) (see section 5.7). These features are also associated with significant mounding on their upper surfaces. The confluence of the two such features is here termed the incised valley. The fill of the SW incision / mound is clearly composite, in cases appearing to have a lower section of downlapping reflectors, onlapped by the overlying reflectors (Figures 5.14. & 5.16), although the internal geometries of the fill vary significantly. Updip (to the SW) the magnitude of incision decreases, and this corresponds to a narrowing of both the pull-up on the base Paleocene reflector, and the width and height of the compaction on the top Sele surface.
In the very southwest of the 3/28 surveys, both the incision and mounding discontinue (Figure 5.24). With respect to the SW canyon, mapping shows the NW mounded feature is much less elongate, and the basal incision cuts down very rapidly. The NW feature discontinues to the west before the edge of the 3/28 dataset. The differences between the two features suggests that they may have different origins.

The incised valley is considerably broader than either of the individual canyons, and shows a chaotic series of internal onlaps and downlaps (Figure 5.25). Dip sections through the valley show that the internal reflectors dip dominantly to the east (Figure 5.26): further to the east, the reflectors have a clinoform geometry (Figure 5.27), and overlie lower angles offlapping reflectors. Extrapolation of the observations in the 9/3 area would suggest that these clinoforms are of Sele sequence age, and the underlying reflectors are of the Forties sequence. An alternative explanation is that the clinoform reflectors indicate yet younger Sele sequence incision, post-dating progradation in block 9/3. The database is insufficient to differentiate between these two alternatives.

Mapping of the top Sele surface demonstrates that mounding over the canyon fills is often asymmetrical (e.g. Figure 5.14) - thicker to south, along strike from the 9/3 high. This could be considered indirect evidence of clinoform progradation post-dating Forties age incision.

### 5.8.3 Block 3/28 - Alwyn Slope

The Paleocene stratigraphy on the Alwyn Slope is thicker than over much of the Bressay area; this is true also for the Forties and Sele sequences if compared to the non-incised areas on the platform. This increase in thickness on the Alwyn Slope is separate from the thickened areas of incision in 3/28 (Figure 5.11). On the Alwyn Slope, the sequence is wedge-shaped in cross section, perched at the edge of the graben, and elongate parallel to strike. The northward extension of this feature is beyond the edge of the data coverage. A dip section of the sequence (Enclosure 28) shows Sele reflectors downlapping to the east; they could be interpreted as clinoforms (particularly towards the east), although no toplap is observed. Onlap of the younger Eocene reflectors occurs from the west and east. The slight westward dip of these reflectors over the updip flank of the high suggests that post-Balder sequence differential compaction took place, and thus that the sequence probably becomes more argillaceous updip.
Figure 5.23. Seismic line SOV-812-37. The mounding displayed in this line is more symmetrical than to the Northeast, as is the top surface of compaction. As in other lines, the base Paleocene reflector loses continuity in the area of mounding. Horizons: Base incision = top Upper Balmoral = dark green; Top Balder = black; Top Sele = dark blue; base Paleocene = lighter green. Horizontal lines are 100ms apart. Width of displayed section 5km. See Figure 5.7b for location.
Figure 5.24. Seismic line SOV-812-43. In this line, the incision and mounding have almost discontinued, and the compaction is again symmetrical. Horizons: Base incision = top Upper Balmoral = dark green; Top Balder = black; Top Sele = dark blue; base Paleocene = lighter green. Horizontal lines are 100ms apart. Width of displayed section 5km. See Figure 5.7b for location.
Figure 5.25. Seismic lines SOV-812-13 (east; lower) & SOV-812-17 (west; upper). These two strike lines illustrate the change from two isolated 'canyons' to a single, broad 'incised valley'. The erosion of the Lower / Upper Balmoral sequences from between the two 'canyons' is observed to correspond with decreased differential compaction occurring between the two mounds. The interpreted red line in the lower figure marks the base of the clinoforms. See text for discussion. See Figure 5.24 for horizon annotation. Horizontal lines are 100ms apart. Width of displayed section 5km. See Figure 5.7b for location.
Figure 5.26. Seismic lines SOV-812-22 (north; upper) & SOV-812-24 (south; lower). Dip lines showing the sharp change in relief at the confluence of the two canyons. The internal character of the mounds is fairly chaotic, but dominantly dips to the east in the lower figure. To the east, the reflectors become clinoforms; c.f. Figure 5.27. See text for discussion; Figure 5.24 for horizon annotation; Figure 5.7b for location. Horizontal lines are 100ms apart. Width of displayed section 7km in upper; 5 km in lower.
Figure 5.27. Seismic line UK85-103 (upper and lower) - clinoform reflectors. This dip line shows that downdip from the main area of mounding, the upper reflectors of the Forties / Sele interval exhibit eastward downlap which could be interpreted as clinoforms. Close to the graben margin (at right hand side of upper diagram), the offlap break of the sequence is observed. Arrows at bottom mark the intersection of lines SOV-27 (Figure 5.14; left hand arrow), SOV-17 (Figure 5.25; middle arrow) and SOV-13 (Figure 5.25; right hand arrow). Horizontal lines are 500ms apart. Width of lower section 5km. See Figure 5.7b for location.
The angle of the graben margin between the Alwyn Slope and the Viking Graben is steep enough to guarantee that slope bypass would have occurred across during the Paleocene. Thus the observed position of the thickened Sele interval is probably due to it being a shelf-edge delta, the natural position of which is as described here, prevented from further progradation due to the rapid oversteepening that occurs at the graben edge.

5.8.4 Velocity Modelling of Paleocene interval

Aims

The magnitude of both the pull-up and the compaction in the 3/28 area were large enough to be modelled in an elementary manner. The well stratigraphy, sonic velocities, and lithology porosities were known. The objective of the modelling was to quantify the lateral change in the volume of sand required to produce the observed pull-up and compaction, in order to test the hypothesis that the lateral change in facies was too great to be a depositional variation.

Model

A model was constructed for a simple sand (S) wedge of variable thickness, incising into an uncompacted shale (Sh1) of thickness T1, which in turn overlay another semi-compacted shale (AndSh) of thickness T2. Each of the units were then compacted by a factor as calculated for a burial depth of 1.2km, and the velocities of each unit calculated to create a synthetic time section. The model was constructed to display the a) start scenario, b) the compacted scenario, using the base of the AndSh as the datum, and c) the calculated time section, using the top sand as a datum (Figure 5.28). See Appendix A for full details.

Data & Assumptions

The following data could be evaluated from well and seismic data:

1) Burial depth
2) Thickness and sand content over the sub-Balder interval (from gamma and sonic logs)
3) Interval velocities of interpreted sequences (from velocity logs)
4) Mean porosities of sands and shales (estimated from sonic logs)
5) Lateral change in time-thickness of interval (measured from seismic sections)

In order to model the seismic sections, a number of gross assumptions were made to simplify the modelling procedure. These were:

1) The units were stratigraphically homogeneous (bulk velocities were used)
2) The starting porosities of sands and shales (following Baldwin & Butler, 1985)
3) That the pull-up and compaction observed was due to one sand body incising Shale 1
4) That the observed mounding was entirely due to differential compaction

The values used for bulk velocities were derived from well data, and were within 2% of the actual means. The compaction of the Sh1 shale (i.e. lateral to Sele incision, where well control was absent) was estimated from the porosity of shales in the respective units in the wells. The starting solidities (where solidity = [1-porosity]) used were after Baldwin & Butler (1985) and P. Farfan (pers. comm.). Compaction was estimated for shales following Baldwin & Butler (1985), given the present depth of burial (about 1.2km) and could be calculated for sands.

Following the construction of this simple model, the model was then scaled to the values derived from well 3/27-1 and seismic line LMO-812-37. For a full explanation of the procedure, see Appendix 1.

**Results & Conclusions**

Initial modelling demonstrated that incision of a sand body into an underlying semi-compacted shale results in a "gull-wing" compaction geometry (Figure 5.29). This model observation reflected the observed seismic data in some cases (Figure 5.30).

The single incision event modelled indicated that the change in compaction and pull-up were due to a lateral change in sand content in the Forties / Sele sequence interval of approximately 300' to 360' total sand (depending on whether the compaction or the pull-up was matched). This was modelled as a single body, 590' thick, comprising 80% sand, cutting into a lithology of 20% sand (Figures 5.31 & 5.32). The magnitude of this lateral change in facies is too great to have occurred depositionally (the orientation of the body is close to dip). Such a thickness of sand could not accumulate
Figure 5.28. Explanation of velocity model diagrams in Figures 5.29, 5.31 and 5.32. Compaction model has datum at zero; velocity model has datum at top of sand. Note that the ‘Andrew Shale’ is probably of Lower / Upper Balmoral age.
without being laterally confined, and thus the change in sand content must have been largely due to incision of the sand-rich body into an underlying relatively sand-poor body. Regional sequence mapping suggests that this may relate to Sele incision.

The number of unconstrained variables only allowed simplistic observations to be made, but the synthetic time section produced by the model deviated from the observed seismic section in the number of important ways:

*The model could not match both pull-up and compaction*

*The modelled single sand body did not incise into the Andrew shale*

The fact that the observed pull-up was greater than required to simply produce the observed compaction probably indicates that the underlying Andrew shale was eroded by the incising sand. This supports the seismic interpretation, and partly explains the failure of the model to match a single sand body to the observed data.

*The modelled sand thickness was less than the well sand thickness*

*The pull-up and compaction are not symmetrical on seismic*

Modelling demonstrates that the compactional and pull-up effects could be produced by a lateral discontinuity / facies change of only part of the sand body observed in well 3/27-1. This suggests that approximately half of the sand body in the well 3/27-1 is laterally continuous. This is consistent with the complex seismic fill of the thickened Forties / Sele interval.
Figure 5.29 Sample of model output demonstrating incision of simple wedge into the Andrew shale. Note the flattening of the top sand on the compaction and velocity models. See text for discussion.
Figure 5.30. Seismic line SOV-812-18 showing the clear "gull-wing" geometry of the top sand / Balder surfaces over the areas of incision. See text for discussion. Horizons: Base incision = top Upper Balmorel = dark green; Top Balder = black; Top Sele = dark blue; base Paleocene = lighter green. Horizontal lines are 100ms apart. Width of displayed section c.5km. See Figure 5.7b for location.
Figure 5.31 Sample of model output demonstrating match of final output with pullup on line SOV-37, constrained by well 3/27-1. The model parameters are: sand content of the main body = 80%; sand content of lateral shales = 20%. See text for discussion. See Appendix 1 for full details of model parameters.
Figure 5.32. Sample of model output demonstrating match velocity model with compaction surface on line SOV-37, as constrained by well 3/27-1. The model parameters are: sand content of the main body = 80%; sand content of lateral shales = 20%. See text for discussion. See Appendix 1 for full details of model parameters.
5.8.5 Incised valley fill

Incised valleys have received much attention in recent years, and although data is lacking to accurately define the valley fill, some simple observations can be made. An incised valley is defined as a fluvially eroded, elongate topographic low, typically comprising more than a single channel, characterised by abrupt seaward shift of depositional facies across a regionally mappable sequence boundary at its base. The fill typically begins to accumulate during the next base-level rise, and may contain deposits of the following highstand and subsequent sea-level cycles (Zaitlin et al., 1994).

The fill in the case here is composite: the basal surface of erosion may also be a composite surface as the interpreted ages indicate re-occupation and re-incision of an older fill. The fill is associated with erosion of the Sele sequence outside the area of incision; lateral Forties erosion and / or hiatus were not identified. The base-level drop implied by the lateral incision, the elongate geometry of the mounds running oblique to paleodip and the high energies implied by the pebble grade material together suggest that the sand-rich facies forming the Bressay discovery are fluvial. The change in incision geometry from narrow, elongate to become wider to the east may indicate two different stages / processes of incision. The factors controlling incision versus avulsion are many and complex (see Thorne, 1994), but the principal factors are considered to be eustasy, tectonics, and fluvial discharge due to climatic change or stream capture (Schumm, 1993). Thorne (1994) suggests that the rate of relative sea-level drop determines whether valleys become entrenched into the lower coastal plain (rapid fall), or the lower alluvial valley (slow fall).

The relative age of the incised valley and the updip 'canyons' is not constrained in this study, but the above factors may have influenced whether the composite incised feature was the result of the updip growth of a platform edge nick-point, or the down-dip expansion of fluvial incision / entrenchment. Zaitlin et al. (1994) propose paradigm fill successions which would distinguish between these alternatives, but uncertainty about the age and the depositional environments of the fill in this case does not allow the evolution of the fill to be determined.

5.8.6 Summary of the Sele / Forties sequences

A number of different hypotheses can be offered to explain the data over the southern 3/28 area. The evidence for base Forties erosion is considered strong, but the
composition and timing of the mound fills is ambiguous. Figures 5.33 and 5.34 present a simple interpretation of the evolution of the Bressay area during these sequences, but the alternatives are outlined in Table 5.1.

Table 5.1. Summary of the alternative interpretations for the Forties / Sele interval

<table>
<thead>
<tr>
<th>Interpretation</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
</table>
| Forties incision sand-rich              | 1) Basal Forties (fluvial) incision would incise Andrew shales and thus produce significant pull-up.  
2) Very clean sands are observed in 3/29. | 1) Preservation of an early incision is a problem as incision continued thereafter.  
2) Incision seen on seismic is small; could accommodate enough sand to produce effects?  
3) Differential compaction over Bressay itself implies incision was into relatively uncompacted shales & expect L Balmoral shale to be compacted |
| Sele incision sand rich                 | 1) Sele incision seen in 9/3, 9/2  
2) Drainage patterns explained | 1) Problem getting enough incision to create pull-up; yet required to get laterally discontinuous sands  
2) Downdip clinoforms same age?  
Shoreline thus in between |
| Incision entirely of Sele sequence age  | 1) Lack of significant lateral incision  
2) Clear lateral Sele incision | 1) Forties sands downdip, but no Sele sands  
2) 'Sele' clinoforms do not reach platform margin |
| 3/28 and 9/3 Sele clinoforms one phase  | Simplest explanation of strike relationship in 3/28 & 9/3 | 1) Incision of Sele west of 9/3 discovery; drainage to where? |

5.8.7 Tectonic controls on incision

The incision on the Bressay shelf occurred during to relative sea-level fall. The magnitude of the sea-level is difficult to establish, but it can be estimated by assuming that any incision associated with the Bressay discovery was caused by the relative sea-level drop. The deviation of the base Paleocene contours from strike seen in Figure 5.19 can thus be used as a proxy for the minimum relative sea-level fall, assuming that
Figure 5.33. A possible evolution of the Forties sequence in the Bressay area.
Figure 5.34. Cartoons illustrating a possible evolution of the Sele sequence in the Bressay area. Partly after Zaitlin et. al. (1994).
the feature is linear due to incision into the underlying Upper Balmoral shales. This gives a estimate for the minimum relative sea-level drop as $100\text{ms+} = c. 100\text{m+}$.

The controls on relative sea-level fall, as discussed above, are complex and cannot be established from the available dataset. However, superposition of the outline of the Bressay granite (as determined by Holloway et al., 1991) on the isochron of the Forties / Sele interval shows a strong correlation between the position of the granite, and the area of incision of the 9/3 discovery (Enclosure 9). This data suggests that local uplift of the granite may have caused the observed changes in fluvial drainage patterns.

Comparison with regional data on the timing of intrusive and extrusive volcanism in the North Atlantic Igneous Province demonstrates that emplacement of the intrusive magmatism into the UK mainland was concomitant with the inception of Forties sedimentation in the North Sea (Enclosure 1). Immediately following the deposition of the Sele Sequence, the Balder volcanic tuff was deposited over much of NW Europe, and this is believed to be contemporaneous with the start of rifting in the Northeast Atlantic (Andersen, 1988; Hitchen & Ritchie, 1993). From the correlation of this data, it is suggested that the change from a compressional to an extensional stress regime immediately prior to the inception of sea-floor spreading in the Northeast Atlantic, allowed the local isostatic re-equilibration and subsequent uplift of the Bressay granite. This in turn influenced the drainage and sedimentation patterns of the Forties and Sele sequences at this time.

In this interpretation, faults previously in compression could have unlocked following the changing regional stress field, and local isostatic re-equilibration of the granite ensued. However, there is no evidence available on regional seismic to show significant reactivation of faults in the area in the Late Paleocene. On the other hand, sedimentation in the Outer Moray Firth / Central North Sea changes around this time: the Outer Moray Firth stops being the main conduit for sediment, and instead influx takes place off Central North Sea graben highs (Den Hartog Jager et al., 1993). In this hypothesis, the Balder sequence transgression continues as the regional stress field equilibrates to the new ocean to the NW, regional subsidence resumes, and true marine circulation in the early Eocene is the last evidence of the regional subsidence.

The fact that incision is observed in the block 9/8 area (Figure 5.6; Milton & Dyce, in press) reinforces the observation in this thesis that the greater Bressay area was
uplifted, but this does not explain the particular change in drainage patterns observed in the Bressay area. Alternative scenarios include:

a) regional uplift controlled by a regional stress field reversing from compressional to extensional;
b) isostatic re-equilibration due to [a]
c) isostatic compensation due to differential erosion and sedimentation on the shelf (J. McGinnis, pers. comm.).

5.9 *Prospectivity of Paleocene on the East Shetland Platform*

The interpreted paleogeography of the Bressay area (Figures 5.33 & 5.34) suggests that fluvial systems incised down into offshore argillaceous sediments as fluvial profiles responded to the observed base-level falls. The resulting abrupt lateral changes in facies led to significant differential compaction upon burial, and the development of four-way dip closures. A by-product of this work has been an insight into the development of such Paleocene hydrocarbon plays on the East Shetland Platform, as discussed below.

The Bressay discovery is the largest undeveloped discovery on the UKCS, estimated at around 800 to 900 million barrels of 16°API oil in place. Along with the 9/3 discovery, these are the only discovery on the East Shetland Platform. This chapter suggests that both discoveries were formed by prograding coastal - marginal complexes that became stranded as base-level fell during the Forties / Sele sequences. Hydrocarbon migration is most likely to have occurred via the graben margin (Hazeldine, 1993).

Modelling supports the hypothesis that lateral dip closure requires the incision of a sand body into a sand-poor stratigraphy. Updip, the sand body either discontinues, or was not preserved (i.e. due to younger erosion). In this area, the reservoir thus has a limited extent, and the lateral and top seals were provided by compacted lateral shales. To the northeast of Bressay, the volume of sand increased, but more importantly incision removed the shales which formed the lateral seal upon differential compaction. Thus although the potential reservoir got larger, the lateral seal discontinued. In the case of the Bressay field, seal potential increases updip where fluvial sands are isolated from marine sands, and where resulting differential compaction is greatest. In principal, similar fluvial plays could occur along the length of the platform.
The isolation of the 9/3 discovery was caused by a change of fluvial drainage leading to strike-parallel drainage. The updip closure was formed by the incision and the subsequent deposition of the Balder shales formed the seal. The preservation of such a body by strike-parallel incision is probably unique, but Dixon & Pearce indicate the isolation of similar bodies updip of the Beryl Embayment due to the development of entrenched fluvial systems on the platform.

5.10 Conclusions

Sedimentation in the Bressay area did not occur contemporaneously with Andrew / Lower Balmoral sequence sedimentation in the Viking Graben and Beryl Embayment, but was initiated following the upper Lower Balmoral transgression of the East Shetland Platform. Lower Balmoral sedimentation switched to become predominantly argillaceous in the East Shetland Basin around this time, although the relative timing of deposition on Bressay and in the East Shetland Basin is not clear.

Forties sequence sedimentation began with the deposition of distal shelf argillites, which were subsequently eroded by regression as relative sea-level dropped. As high energy fluvial / coastal regimes encroached upon the edge of the platform, incision into the underlying Lower Balmoral sequence took place in the north. Continued incision formed a conduit for Forties sediments to pass off the shelf, and prevented the complete removal of the sand body in the area of the 9/3 discovery. The Forties fluvial systems instead became entrenched and fed sediments directly downdip to around block 3/29. The Forties sequence was subsequently transgressed.

During the Sele sequence, relative sea-level fall again occurred, causing regression of the shelf sediments, and driving eastward progradation of the Sele sequence in the Bressay area. However, relative sea-level drop was at least partly due to local tectonic uplift of the Bressay granite underlying block 9/3. This interfered with the prevailing drainage patterns, and caused incision of the area west of the 9/3 discovery. This incision drained to the north through 3/28.

Subsequent differential compaction of the Forties and Sele sequences formed two four-way closures in block 3/28, which became traps for oil migrating from the deeper Viking Graben to the east.
Chapter 6
Summary & Conclusions

6.1 Introduction

Chapter 6 reviews the preceding 3 chapters and places the observations therein into a regional context. The objectives of this chapter are to integrate the different scales of observation and compare the interpretations made here with the previous work in the Northern North Sea and further afield. The chapter first reviews the methodologies used and then describes the stratigraphic evolution of the Northern North Sea.

6.2 Discussion of methodologies

Seismic and sequence stratigraphy are widely used in seismic and well log interpretation, but the associated models (e.g. Payton, 1977; Posamentier & Vail, 1988a; Posamentier et al., 1988; Van Wagoner et al., 1990; Posamentier & James, 1993) are still evolving (e.g. Miall, 1986 & 1992; Galloway, 1989a, b; Walker, 1990; Cartwright et al., 1993; Underhill & Partington, 1994). This section examines possible interpretations of the data presented in the thesis.

6.2.1 Seismic stratigraphy

The tie between the seismic stratigraphic interpretations and well log data was generally good on both paper and digital seismic data. The corroboration of seismic data by well log data was key as the Paleocene reflectors were commonly discontinuous and of low reflectivity. The synchronicity of seismic reflectors has been questioned (Aubry, 1993; Tipper, 1994) but the resolution of this dataset was not sufficient to replicate this work.
In the Ninian 3D seismic data the boundary between the 2 composite lobes is disconformable, as demonstrated by the angular discontinuity at the boundary on horizon slices and the changing reflector geometries on vertical seismic lines. It is suggested that the discontinuity at the lobe boundary is both erosional and hiatal (at a seismic scale) but that magnitude of both the erosion and hiatus varies along strike. This is consistent with the progressive onlap of the younger lobe indicating a variable seismic hiatus and the limited occurrence of mounded reflectors indicating variable erosion. It is further supported by the changing well log character between the lobes.

The reflector patterns seen at the boundary of the two lobes are similar to those observed in Tesson et al. (1993) (section 4.9.3; Figure 4.17), which were attributed to sea-level fluctuations. The deposition of successively lower topsets is suggested by 2D regional data but equally this could be due to compaction effects. Differential compaction at the edge of the lobes in the 3D survey (section 4.8.2; Figures 4.6 & 4.7) probably reflect the changing sand content of the lobes and could indicate regression.

No clear evidence of base-level fluctuation was observed in the 3D dataset and the change in reflector dip and angle between the two lobes could therefore be interpreted as a change in sediment flux and / or avulsion. In contrast, Suter et al. (1987) noted that high-frequency deltaic cycles could be produced autocyclically. It is not possible to isolate the causes of autocylicicity from the available data. Access to several 3D seismic datasets in the area would potentially allow discrimination between local progradation (autocyclic) and more regional progradation indicating a relative base level fall.

The interpretation of the observed seismic geometries was thus ambiguous, even with the available high density well and 3D seismic dataset, but discontinuities probably dominate the temporal extent of the data (Ager, 1993; Cartwright, 1993). The restricted temporal extent of the delta lobes together with their limited areal extent prevented regional correlations and the application of seismic or sequence stratigraphic analysis within the clinoform interval.

6.2.2 Lithostratigraphy & Biostratigraphy

Log Picks

The sequences in this study were principally defined on biostratigraphic criteria. Outside the areas of good biostratigraphic control, correlation was made on other
criteria (Table 6.1). In such situations log picks were usually made on gamma / sonic highs associated with shales which were considered laterally more continuous than the sands in this basinal setting.

Table 6.1. Lithostratigraphic picks used where biostratigraphic control was absent.

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Biostratigraphic definition</th>
<th>Lithostrat. definition (base)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maureen</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base</td>
<td><em>P. americana (O.lens)</em></td>
<td>Uphole decrease in sonic; mixed</td>
</tr>
<tr>
<td>Top</td>
<td><em>E. Trivialis, G. Cf. compressa S.Blow</em></td>
<td>arenaceous &amp; carbonates</td>
</tr>
<tr>
<td></td>
<td></td>
<td>lithologies</td>
</tr>
<tr>
<td>Andrew</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base</td>
<td><em>P. bulliforme acme</em></td>
<td>Incoming sands; diverging sonic and gamma logs</td>
</tr>
<tr>
<td>Top</td>
<td><em>Thalassiphora Cf. delicata</em></td>
<td></td>
</tr>
<tr>
<td>L. Balmoral</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base</td>
<td><em>Q. allomorphinoides (Cenodiscus SP.1 RRI acme)</em></td>
<td>Increasing sonic; decreasing gamma and consistent sands. Sands</td>
</tr>
<tr>
<td>Top</td>
<td><em>P. pyrophorum (P. bulliforme?; S. membranospina?)</em></td>
<td>and shales becoming more discrete</td>
</tr>
<tr>
<td>U. Balmoral</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base</td>
<td><em>L. obscurum</em></td>
<td>Following top LB sand in East</td>
</tr>
<tr>
<td>Top</td>
<td><em>A. margarita</em></td>
<td>Shetland Basin; consistent resistivity, gamma and sonic logs.</td>
</tr>
<tr>
<td>Forties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base</td>
<td><em>Rhizammina/Bathysiphon</em></td>
<td>Incoming sand in East Shetland Basin after top Upper Balmoral</td>
</tr>
<tr>
<td>Top</td>
<td><em>A augmentum acme</em></td>
<td>gamma / sonic high; diverging sonic &amp; gamma logs</td>
</tr>
<tr>
<td>Sele</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base</td>
<td><em>A. augmentum, Apectodinium spp. (acme)</em></td>
<td>Diverging sonic &amp; gamma logs after top Forties shale</td>
</tr>
<tr>
<td>Top</td>
<td><em>C. wardenensis acme</em></td>
<td></td>
</tr>
<tr>
<td>Balder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base</td>
<td><em>D. oebisfeldensis acme</em></td>
<td>Base &amp; top: on strong gamma peak associated with strong sonic low</td>
</tr>
<tr>
<td>Top</td>
<td><em>Coscinodiscus sp.1, 2 Bart</em></td>
<td></td>
</tr>
</tbody>
</table>

In the areas of good data coverage, sequences were defined using biostratigraphic data. This was then convolved with multiple wireline log data to identify a consistent log pick. Outside the area of good biostratigraphic data, an example of the difficulty of
lithostratigraphic correlation is the base of the Upper Balmoral sequence. Well and seismic correlation indicated that the lower boundary of the sequence was approximately equivalent to the top of the underlying Lower Balmoral sands in the East Shetland Basin. However, such a lithostratigraphic pick was incorrect in the Viking Graben area, where the Lower / Upper Balmoral boundary was a shale-on-shale contact. The identification of the lower boundary was thus at times subjective.

Log pick interpolation

As noted by Armentrout et al. (1993), identifying regionally significant sequence surfaces in stacked sandstones is difficult because of sand-on-sand contacts. Correlations are thus dependent on regional seismic horizons or biostratigraphic data which are often facies controlled and not chronostratigraphically reliable. This was true in this work, for instance at the Lower / Upper Balmoral boundary (e.g. 2/10-1, Enclosure 16) and at the Upper Balmoral / Forties contact where both sequences were sand-prone (e.g. Enclosure 11). Variations in log character were also insufficient to allow the differentiation of sequences at shale-on-shale contacts (e.g. the Upper Balmoral and Forties / Sele sequences in the west of the East Shetland Basin, section 5.5.6). In these cases, boundaries were either identified only tentatively, or interpreted by interpolation of vertical log trends.

6.2.3 Sequence stratigraphic considerations

6.2.3.1 Variable character of sequences

The biostratigraphic framework described here for the Northern North Sea identifies seven depositional sequences, each separated by a depositional break, or a hiatal interval (Neal et al., 1994). Such hiatal or condensed intervals are commonly considered to be represented by correlatable gamma highs in distal settings (e.g. Loutit et al., 1988; Galloway, 1989a; Underhill & Partington, 1994; Figure 6.1), and this hypothesis was tested in the study.

When observed in detail, the log character of gamma highs was observed to vary considerably. Furthermore, the correlation between gamma maxima and biostratigraphic hiatus (defined in areas of good data quality) was not always high. Thus it was questioned whether the correlation of gamma highs as effectively isochronous markers was valid in the Paleocene of the North Sea. This could not be easily tested in
Figure 6.1. Diagram comparing the Exxon and Galloway sequence stratigraphic methodologies (from Underhill & Partington, 1994). The ideal cases illustrated here were not always observed in this study. Compare with Figure 2.7.
a dataset with no core data and only limited biostratigraphic control, but two lines of argument are presented below.

**Gamma ray spectrometry work**

Gamma ray spectrometers break down the total gamma count and identify the proportion of the total count from the constituent components: Uranium, Thorium, and Potassium. Such work demonstrates that although the Uranium (U) and Thorium (Th) concentration of condensed sections does rise above that normally observed, the falling Potassium (K) content more than offsets the increased gamma count of the U & Th. This is because K is a beta particle emitter, whereas both U & Th emit less energetic alpha particles when decaying. Work by Davies (1994) and K. Stephen (pers. comm.) illustrates that often the highest total gamma count (as read by gamma logs) can occur a few tens of feet from the most condensed section.

In core 3/3-11 (section 4.8.4; Figure 4.9), the gamma high at the base of the sequence correlated with a tuffaceous claystone, whereas the top of the most condensed, fissile claystones (i.e. the candidate condensed section) coincided with the drop in the sonic log. The offset between the gamma maxima and the observed condensed section in the core was approximately 20'.

**Graphic Correlation data**

Examination of Enclosures 5 and 6 illustrates that whereas some gamma maxima can be approximately correlated with hiatal intervals as identified by Graphic Correlation (e.g. the Forties / Sele boundary in well 9/3-1; the Lower / Upper Balmoral contact in well 3/23a-2), other significant hiati do not correlate with gamma highs (e.g. the Lower / Upper Balmoral contact in well 9/4-1). Furthermore, the relative magnitude of the gamma peaks observed in these wells does not always tie with breaks in sedimentation (compare the Lower Balmoral shales in well 3/23a-2 with those above). Thus, the premise that gamma highs are necessarily hiatal intervals, and by implication isochronous surfaces, was not an assumption that was made when correlating sequences in this study.

The uphole lithological character changes at the boundary between sequences also varied, from sand to sand (e.g. Andrew / Lower Balmoral sequences), shale to sand (e.g. the Upper Balmoral / Forties sequences in 3/29-2), sand to shale (e.g. the Sele /
Balder sequences) and shale to shale (e.g. the Lower Balmoral / Upper Balmoral sequences in 9/8-4). Furthermore, as demonstrated for the Andrew / Lower Balmoral sequences, the timing of sand deposition within individual sequences can vary laterally (section 3.5.3).

It is argued therefore that in a distal depositional environment such as the North Sea, the character of the sequences, their boundaries, and hence their wireline log profiles are controlled by spatial and temporal variations in sedimentation. In a depositional environment experiencing uplift and a high sediment flux, condensed sections may be suppressed, although sequence boundaries would not necessarily be enhanced. This situation is corollary of that described by Underhill & Partington (1994) who suggested that basins undergoing rapid subsidence would be marked by a relative suppression of sequence boundaries, and enhancement of maximum flooding surfaces. The difference in depositional environments that allows maximum flooding surfaces to be used effectively in the Jurassic but not in the Paleocene probably is related to a relatively higher sediment flux in the Paleocene, preventing full sediment starvation. Thus in the Paleocene there are few claystones which do not contain fine arenaceous sediment.

Recognition of condensed sections is complicated by the occurrence of periods of sediment starvation other than at the times of maximum flooding on the shelf (Vail & Wornardt, 1991; Powell, 1992a). The identification of condensed sections on wireline logs in the basin without updip corroboration therefore requires the identification of a regional event, and some circumspection. Nevertheless, the identification of consistent trends in shales is important in identifying the boundaries to sequences in a distal depositional environment (section 6.2.2).

6.2.3.2 Controls on deposition

Examination of Enclosure 27 and Table 3.1 illustrates that the seismic reflector relationships in the Paleocene of the Northern North Sea are dominated by westward onlap against the graben margins, and eastward downlap into the basins (Enclosure 10). A number of authors (Milton et al., 1990; Jones & Milton, 1994; Neal, 1994) have noted the character of the Paleocene in the Outer Moray Firth and Central North Sea, and interpreted the stratigraphy as being the result of the interaction of long duration tectonic cycles (2nd order of Vail et al., 1991), and shorter duration sea-level changes. This conclusion was reached by identifying systems tracts within the data.
The seismic geometries observed in the Northern North Sea may alternatively be viewed in the light of sediment supply as a control. This is considered valid, given that modelling implies that sediment supply, eustasy and tectonics are interchangeable variables (Burgess, 1994), and variations in sediment supply can result in changes of the same order of magnitude as eustasy or tectonics (Boyd et al., 1988; Weimer, 1989; Mutti, 1992). Furthermore, the abrupt changes in sediment supply and calibre into the North Sea basin reflects the rejuvenation of the North Sea hinterlands (e.g. Knox et al., 1981; White, 1988; Thomson, 1993; Brodie & White, 1994). The demonstrable change in depositional gradient from the platforms to the basins, and the supporting core data implies that - until the graben structures were infilled - sediment supply into the East Shetland and Viking Graben basins would be supplied by density current processes (in addition to background sedimentation).

Given the sharp changes in bathymetry, it is suggested that significant changes in sediment flux could generate the observed stratigraphy. At a seismic scale, the reflector geometries record an influx of sediment into the basin and record no information about base-level prior to deposition of the Forties sequence. The shifting arenaceous supply during the Andrew / Lower Balmoral sequences from the Beryl Embayment / Viking Graben to the East Shetland Basin (section 5.5.3) implies that relative transgression may have taken place in the Bressay area, whilst regression occurred to the north. The interpretation of this is that fluvial drainage patterns on the East Shetland Platform changed sharply and moved the principal arenaceous sediment supply to the north. A thick argillaceous succession was coevally deposited in the southern East Shetland Basin. This is consistent with the provenance studies of Morton et al. (1993). Thus, whilst relative sea-level changes may have been influential, shifts in the drainage patterns on the shelf can be demonstrated to have controlled deposition in the basin.

The subdivision of the Paleocene stratigraphy into systems tracts has been attempted by many authors (e.g. Stewart, 1987; Den Hartog Jager et al., 1993; Armentrout et al., 1993; Morton et al., 1993; Jones & Milton, 1994; Neal, 1994). However, in this study application of these terms is considered misleading, bearing in mind that systems tracts "explicitly involve interpretations regarding sea-level change" (Posamentier & James, 1993). There are four principal reasons for this:

a) If the system is supply driven, then deposition in the basin would have occurred at any sea-level. Given that the seismic character of the Andrew / Lower Balmoral sequences resulted from sediment ponding against the structural break
in slope, the resulting onlap / downlap patterns would occur when sediment advanced to the edge of the platform regardless of sea-level position.

b) Systems tracts are composed of parasequence sets, and defined by the stacking patterns within these sets: whether they are progradational, aggradational, or retrogradational (Posamentier et al., 1988; section 2.6). However, the Andrew / Lower Balmoral sequences were deposited by mass flow processes, so the observed stacking patterns are the result of certainly secondary, and possibly tertiary deposition (core 2/10a-6 implies proximal oversteepening leading to mass flow into basin). The interpretation of stacking patterns in terms of systems tracts is thus questionable.

c) If the transgression in the Beryl Embayment / Viking Graben area is coeval with regression in the East Shetland Basin, then stacking patterns in the two areas would imply different systems tracts.

d) In the case of the Ninian delta system, as the entire interval is diachronous, vertical stacking patterns record the development of only a small portion of the delta. Stacking patterns in wells thus record changing patterns of delta-front supply / wasting, and not a regional change in sediment supply.

Relative sea-level changes did occur in the basin, as recorded in the London-Hampshire basins (see section 6.7.2). Tectonism also is well documented, for instance the uplift and tilting of the Outer Moray Firth (Jones & Milton, 1994), the uplift of the basin margins (e.g. Hillis et al., 1994), and the shifting pattern of sediment provenance (Morton et al., 1993). The interaction of these factors with sediment supply changes (e.g. grading & development of the hinterland; river avulsion, Schumm, 1993) is anticipated, and in the study area, the interpretation of systems tracts (i.e. a sea-level control) is not considered to be suitable because sea-level is only one amongst many factors.

In summary, a sharp change in gradient at the basin margin can produce proximal onlap / distal downlap seismic geometries, and the facies recorded in the basin do not define stacking patterns necessarily related to base level change. Thus local changes in sedimentation may drown any eustatic signal, and should not be misinterpreted as being of more regional significance (Underhill, 1991).
6.3 Overview of Hinterland & Basin Characteristics

The Paleocene was an interval of very significant clastic influx into the East Shetland Basin, consistent with suggestions that deposition occurred during hinterland uplift (Jones & Milton, 1994; Enclosure 2). The characteristics of the Orkney / Shetland Platform supplying the sediment are relatively unknown, but most of the area was exposed during the Paleocene, recycling the older sediments on the platform (e.g. Morton, 1979; Morton et al., 1993). The fluvial regimes that drained the platform must also have received significant volumes of sediment from the Orkney-Shetland region, a total hinterland area of approximately 35,000km$^2$. The uplift of the hinterland increased to the west: Jones & Milton (1994) estimated uplift of 800m in the Outer Moray Firth, whereas velocity analysis and fission track data suggests 1 to 2 kilometres in the Inner Moray Firth (Thomson, 1993; Den Hartog Jager et al., 1993). The change in depositional patterns in and around the East Shetland Basin during the Paleocene (this study; Heritier, 1979; Morton, 1982; Mudge & Bliss, 1983; Morton et al., 1993) contrasts with the patterns of Paleocene sedimentation in the Inner Moray Firth-Outer Moray Firth (Figure 6.2), which was the conduit for all the arenaceous sedimentation reaching the Central North Sea or Viking Graben. These differences, and the patterns of provenance evolution (e.g. Knox et al., 1981; Morton et al., 1993) imply changing drainage patterns off the East Shetland Platform. Volcanogenic sedimentation also occurred, but it was not a significant proportion of the total sediment volume.

The receiving East Shetland Basin was a thermally subsiding post-(failed) rift basin (Thorne & Watts, 1989), uplifted on the western margin. Remnant topography dating from the Jurassic rifling probably influenced sediment distribution rather than continuing subsidence (section 5.5.6). Variations in tectonic subsidence in the basin associated with concomitant margin uplift have not been quantified.

6.4 Maureen sequence

Age Late Danian

The Maureen sequence as described here correlates with the Maureen Formation of Mudge & Bliss (1983). The base of the unit as identified by biostratigraphic control agrees closely with that interpreted by Den Hartog Jager et al. (1993) and Neal et al. (1994), but the temporal extent of the sequence in the Northern North Sea is considerably shorter than that described by these authors for the Central North Sea (Enclosure 3). This may be due to the relatively small number of wells recording
Figure 6.2. Correlation of the Paleogene of the Central and Northern North Sea (from Knox & Holloway, 1992).
Maureen deposition in this study or, alternatively may indicate a real difference between the Central and Northern North Sea. The interpretation of a shorter period of Maureen deposition in the East Shetland Basin would be consistent with the relatively thin deposits observed in the basin with respect to the Outer Moray Firth (Johnson, 1987; see section 5.5.2). As noted in chapter 4, no deposition of Maureen age occurred in the Bressay area (Figure 6.3).

The oldest Paleocene sediments in the central North Sea comprise the Ekofisk Formation, also of Danian age (Enclosure 3). These sediments extend across the Central North Sea and Viking Graben, becoming increasingly argillaceous to the north (Mudge & Bliss, 1983). However, graphic correlation evidence suggests that no significant deposition occurred prior to the Maureen sequence in the study area. The absence of any Ekofisk Formation strata in the Northern North Sea implies that the duration of the Cretaceous / Tertiary unconformity increases to the north in basinal areas.

6.5 Andrew / Lower Balmoral sequences

Age: Selandian to early Thanetian

This work differentiates the Maureen and Andrew / Lower Balmoral sequences in the study area (section 5.5.3). In doing so, the mapped distribution of the Maureen and Andrew / Lower Balmoral sequences varies from that of previous publications (Heritier et al., 1979; Morton, 1982; Mudge & Bliss, 1983; Knox & Holloway, 1992; Mudge & Copestake, 1992b; Morton et al., 1993). The biostratigraphic definition of the Andrew / Lower Balmoral sequences (section 5.4) also varies from other stratigraphic frameworks (e.g. Mudge & Copestake, 1992a; Den Hartog Jager et al., 1993; Neal et al., 1994; Jones & Milton, 1994; Enclosure 3). Comparison of these frameworks suggests that the main clastic influx into the Northern North Sea basin occurred coevally with (Den Hartog Jager et al., 1993), or later than (Neal et al., 1994) Andrew deposition in the Central North Sea. The events identified in the Northern North Sea correlate well with the mineralogical changes identified by Morton et al. (1993) (Figure 6.3). However, with the exception of the Maureen interval, the source terranes of Morton et al. (1993) remained relatively isolated, implying separation of the fluvial regimes draining the northern and southern areas of the East Shetland Platform.

No evidence for active faulting along the platform margin is observed in the study area, either divergence of seismic reflectors (section 3.5.3; Figure 3.8), or direct imaging of
Figure 6.3. N-S and W-E cartoons illustrating the chronostratigraphic development of the northern North Sea. Details of the mineralogical scheme of Morton et al. (1993) are also included, including source terranes. (N= North; C= Central; S= South East Shetland Platform).
a fault. This agrees with previous work by Condon (1988) and Badley et al. (1988) and Bertram & Milton (1989). Badley et al. (1988) suggested that movement of the fault took place during or immediately after clastic deposition, and was driven by differential compaction across the old fault topography. The abrupt change in sediment supply is instead tectonic uplift of the hinterland.

The overall scale of the Andrew / Lower Balmoral clastic system is broadly similar to a turbidite system as defined by Mutti & Normark (1987). The Andrew / Lower Balmoral system differs from Mutti & Normark's description in lacking channels or canyons. The two main arenaceous systems in the Viking Graben and East Shetland Basin can be thought of as separate systems; the thick lateral claystone sequences are equivalent to the marginal wedges of Mutti & Normark (1987, 1991). In terms of duration, deposits of comparable size have formed considerably more rapidly than can be biostratigraphically resolved. For example, in the Pliocene and Quaternary of the Mississippi, systems up to 800m thick and 500km in length formed in less than 0.1 My (Boyd et al., 1988; Weimer, 1989). The same temporal scale (0.01 to 0.1 My) can be assumed for some tectonically-controlled turbidite systems in fold-thrust belts (Mutti, 1992).

The absence of evidence of fault movement, together with the very sharp change in sediment character and supply from the underlying deposits, and the evidence of shifting depocentres indicates a major change in sediment supply to the basin. Given the regional setting, the most likely cause for this distinct change is tectonic uplift of the hinterland (e.g. Jones & Milton, 1994; Milton et al., 1990). Deposition during the Andrew / Lower Balmoral sequence probably resulted from the establishment of fluvial drainage systems following the re-equilibration of the hinterland to the uplift.

The deposition of the Andrew / Lower Balmoral sequences in the Northern North Sea is typical of their distribution in the North Sea generally. As elsewhere, the Andrew / Lower Balmoral clastic influx is preserved in a number of distinct depocentres: in the South Viking Graben, the Witch Ground Graben, and the Outer Moray Firth (e.g. Mudge & Bliss, 1983, Knox et al., 1981). Jones & Milton (1994) demonstrated a total relief of about 600m on the Andrew to Forties sequences in the Outer Moray Firth, locally incising up to 300m (Enclosure 2).
6.6 Forties & Sele sequences

Age: Mid- to late Thanetian

The depositional processes and genetic relationships of the Ninian delta are described in detail in chapters 4 and 5. Integration of the observations in the Bressay area and the East Shetland Basin are hampered by the absence of biostratigraphic data over the interval. The main progradational sequence was described as being Sele Formation age (Forties / Sele sequence) age by Mudge & Copestake (1992b). Circumstantial evidence in the data supported this: despite evidence of two base-level falls in the Bressay area, evidence for only one clear progradation was observed in the East Shetland Basin. An alternative interpretation is that the 'topset' sands of the Ninian delta are in fact of Sele age, as opposed to the underlying Forties age clinoforms. This interpretation does not tie well with the limited biostratigraphic data in the southern part of the East Shetland Basin, but the issue could not be resolved with the available data.

There is little direct evidence of significant faulting or mass movement acting in the Ninian delta, although it may be significant at a sub-seismic scale. Equally, quantification of the basin subsidence and hinterland uplift is difficult. The available evidence suggests that basin subsidence was relatively even by Forties / Sele sequence times, but still slightly greater over the Jurassic faults. Evidence of significant hinterland uplift decreases to the north of the East Shetland Platform, both in terms of observable features on seismic (R. Anderton, pers. comm.), and the decreasing volume of the delta in the northern East Shetland Basin. Modelling of these parameters might be able quantify these observations further.

Table 6.2 compares the Ninian delta to a number of other modern deltas. The estimated statistics for the Ninian delta are reasonably well constrained in each case, with the exception of river length (the length of the flowline of the main stream of the catchment from its headwaters to the rivermouth), which is an estimate based on a river extending across the East Shetland Platform from the southwest. With these caveats, the statistics indicate that the Ninian delta is broadly equivalent in size and sediment calibre to its modern equivalents, although it is suggested that the river and basin length may be shorter than would be observed in a modern analogue. This may imply a relatively steep hinterland gradient, which would be expected given the rapid tectonic uplift reaching its zenith at the time of Ninian deposition.
Table 6.2. The Ninian delta compared to some modern deltas.

<table>
<thead>
<tr>
<th>Delta</th>
<th>Type</th>
<th>Drainage Area (10^3 km^2)</th>
<th>Grain Size (mm)</th>
<th>Delta Plain Area (km^2)</th>
<th>Water Depth (m)</th>
<th>River Length (km)</th>
<th>Basin Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC Bella Coola</td>
<td>GS iw</td>
<td>4.2</td>
<td>0.5-20</td>
<td>5</td>
<td>600</td>
<td>--</td>
<td>662</td>
</tr>
<tr>
<td>CV Colville</td>
<td>GS</td>
<td>59.5</td>
<td>0.02-10</td>
<td>1687</td>
<td>--</td>
<td>360</td>
<td>325</td>
</tr>
<tr>
<td>CP Copper</td>
<td>FS wt</td>
<td>60.0</td>
<td>0.25</td>
<td>1920</td>
<td>150</td>
<td>930</td>
<td>470</td>
</tr>
<tr>
<td>EB Ebro</td>
<td>FS iw</td>
<td>85.8</td>
<td>0.20</td>
<td>325</td>
<td>100</td>
<td>--</td>
<td>350</td>
</tr>
<tr>
<td>HM Homathko</td>
<td>GS it</td>
<td>5.72</td>
<td>0.14</td>
<td>3</td>
<td>550</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>KK Klinaklini</td>
<td>GS i</td>
<td>6.5</td>
<td>0.1-1.0</td>
<td>6</td>
<td>350</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>NN NINIAN (GS)</td>
<td>35</td>
<td>=0.05-5.0</td>
<td>c. 1800</td>
<td>(200-300)</td>
<td>&lt; c.300</td>
<td>c. 150</td>
<td></td>
</tr>
<tr>
<td>OD Ord</td>
<td>MS t</td>
<td>78.0</td>
<td>0.176</td>
<td>3896</td>
<td>--</td>
<td>--</td>
<td>400</td>
</tr>
<tr>
<td>PO Po</td>
<td>FS i</td>
<td>71.7</td>
<td>0.52</td>
<td>13398</td>
<td>--</td>
<td>691</td>
<td>480</td>
</tr>
<tr>
<td>RH Rhône</td>
<td>FS wi</td>
<td>90.0</td>
<td>0.08-0.5</td>
<td>2540</td>
<td>50-100</td>
<td>810</td>
<td>540</td>
</tr>
<tr>
<td>SH Shoalhaven</td>
<td>FS m</td>
<td>7.25</td>
<td>0.25</td>
<td>85</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>TB Tiber</td>
<td>FS w</td>
<td>17.16</td>
<td>silty-sand</td>
<td>250</td>
<td>150</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

* Note that the calculated river length for the Ninian delta is a guesstimate, based on the predicted six of the hinterland.

---

a GS = gravel & sand; FS = fine sand; MS = mud / silt; i = input dominated; t = tide dominated; w = wave dominated; m = mixed. From Orton & Reading (1993)
b The surface from which a river collects surface runoff, including the peripheral zones which only contribute runoff in cases of exceptional rainfall. From Orton & Reading (1993)
c Grain size, mean or range. From Orton & Reading (1993)
d, e From Orton & Reading (1993)
f Length of the flowline of the main stream of the catchment from its headwaters to the rivermouth. From N. Hovius (in press).
g The maximum length of the drainage basin in the direction of the main stream. From N. Hovius (in press).
6.7 Comparison with other areas

6.7.1 Outer Moray Firth / Central North Sea

**Pre-Forties sequences**

The distribution of the pre-Forties sequences in the Outer Moray Firth is similar in general style to that seen in the Northern North Sea, given the clear difference in underlying structure of the grabens. Both demonstrate thick wedge profiles, thickening and onlapping marginward (e.g. Jones & Milton 1994). In the Outer Moray Firth, Jones & Milton interpreted incision into the T30 (Lower / Upper Balmoral) sequences, down to approximately 500ms time-depth, i.e. about 500ms above the structurally highest deposits in the study area.

Inconsistencies between the stratigraphic framework used here and that of others does not allow the relative age of the main clastic influx into the Northern North Sea to be resolved. Any differences could indicate real changes in the evolution of the hinterland uplift. However, given the poor resolution of the biostratigraphy in the North Sea, it must be questioned whether a gap of 500,000 years or so (the available resolution) would be sufficient to differentiate the timing of sediment influx into these basins, given the short timescale over which they can develop (0.01 to 0.1 My; section 6.6).

**Forties and Sele sequences**

As noted by Milton *et al.* (1990) and Jones & Milton (1994) basinal fans and not progradational wedges were generally preserved during uplift in the Outer Moray Firth (T20 to T40 sequences), whereas thick shelf-margin wedges were preserved during the tilting and subsidence phases (T45 sequence). On the basin margins during deposition of the Dornoch, Beauly and an ultimate shelf-margin wedge, margin uplift continued whilst subsidence simultaneously increased in the basin, and encroached to the west (i.e. the area of uplift narrowed). In the basin, the Forties sandstone in the Forties field is conformable with the overlying Dornoch-equivalent hemipelagic mudstones (Stewart, 1987).

The change from turbiditic to shelf-margin deposits is also observed in the Northern North Sea. The fact that this coincided with the acme of tectonic uplift of the hinterland implies that the basinward shift of coastal onlap occurred principally due to narrowing
of the basin. Preservation of the shelf margin systems was probably influenced by the abrupt shelf break at the platform margins creating accommodation space in the basin (Trincardi & Field, 1991). In contrast to the Outer Moray Firth deltaic succession, the East Shetland Basin succession probably lacked a fluvial drainage system directly updip. This implies that the distribution of the Ninian delta deposits were probably more influenced by the controls of sediment supply and sediment dispersal, with respect to the Outer Moray Firth deltaics. These observations are consistent with data presented, and suggest that the bulk of the Ninian delta was preserved following a change from forced to normal regression caused by base-level reaching the break in slope at the platform margins. This contrasts with the interpretation of Den Hartog Jager et al. (1993), who envisaged forced regression being a control throughout deposition of the delta.

There is no equivalent to the widely distributed Forties sandstone of the Outer Moray Firth in the Northern North Sea. The local distribution of the Forties sandstone in the block 3/29 area represents an isolated example of the Forties sands prograding off the East Shetland Platform (Mudge & Copestake, 1992b; Dixon & Pearce, in press). This difference is partly due to the sharp slope changes in the Northern North Sea, which were not present in the Outer Moray Firth where a shelf-margin system had prograded down the course of the graben. However, it is of note that although the Forties sequence is the time of maximum uplift of the basin margin, it is not associated with the maximum regression in the basin. This implies that sediment supply into the basin was not directly related to the magnitude of margin uplift in the Northern North Sea. Alternatively, this may be due to the Outer Moray becoming the principal sediment input point for the entire basin, and the Northern North Sea receiving sediment mainly by alongshore drift.

The absence of basinal sands associated with the Forties and Sele systems was noted by Galloway et al. (1993). They suggested that decreased sediment remobilisation may have arisen from decreased bathymetric relief, a decrease in seismic activity, or a decreased sediment supply, and inhibited sediment bypass into the basinal areas. It is true that once into the basin, bathymetric slopes are smaller. Other alternatives suggested here are:

a) Increased grain calibre resulted in more stable delta-front slopes, and decreased efficiency. This could have resulted from the more basinal position of the fluvial systems, possibly combined with the lack of winnowing and sorting that would
have previously occurred across the broad, open shelf of the East Shetland Platform.

b) The narrowing of the basin as described by Milton et al. (1990) resulted in a decreased paleoslope in the basin

c) The isolation of the basin during the Forties and Sele sequences resulted in a change in current patterns and/or basinal energy.

6.7.2 UK onshore & the British Tertiary Igneous Province

White (1988) suggested that the opening of the Northeast Atlantic was accompanied by dynamic lithospheric uplift, associated with the impingement of a hot, upwelling plume in the (now) Iceland area. Circumstantial evidence would suggest that the uplift of the UK mainland was associated with this event.

Looking at the timing of the igneous activity, with the exception of the Muck, Eigg, Rum and Canna extrusives (Hitchen & Ritchie, 1993), the initiation of activity in the British Tertiary Igneous Province did not start until after the end of Maureen Sequence deposition (Enclosure 1). This is supported by Watson (1985), who noted that where thin Cretaceous greensands are locally present under lavas in Arran, Mull, Eigg, Raasay, Skye and in Antrim, they were not stripped off by any uplift prior to extrusives. The remaining extrusives (in Blackstones, Mull, Ardnamurchan, Skye, the Hebrides Terrace, Arran, Ireland and Lundy) were erupted by the end of the Lower Balmoral sequence. The youngest of the intrusives in these areas (in Blackstones) are dated as being coeval with the start of Forties sequence deposition.

Onshore in southern England, the oldest stratigraphy is approximately coeval with the upper Lower Balmoral sequence, suggesting that the Danian uplift demonstrated for many areas of the UK (e.g. Green, 1989) also affected the London / Hampshire basins. The magnitude of the uplift on onshore UK, and the similar age of the hiatus in the South of England and the North Sea suggests a period of non-deposition / erosion, and supports the idea of regional uplift caused by the convergence of two compressional stress fields from the Alps and NW Atlantic (e.g. White, 1988, Zeigler 1987b, etc.).

Precise correlation of the onshore and offshore sequences is still beyond the resolution
of present biostratigraphic data (Powell et al., 1994), but Enclosure 1 illustrates that more transgressive-regressive cycles are recognised in outcrop than offshore. This is not surprising given the relatively poorer data obtained offshore. The correlation of the onshore sequences is outside the scope of this study, and is the subject of much ongoing research (e.g. Ellison et al., 1994; Jolley, 1994; Neal et al., 1994; Knox et al., 1994; Bujak and Mudge, 1994). However, following Miall (1992), it is noted that the two areas need not be co-equivalent.

### 6.8 Conclusions

A new, high-resolution stratigraphic framework is presented for the Northern North Sea, demonstrating that deposition in the area occurred in at least seven depositional episodes or sequences, bounded by hiatal intervals. The depositional framework is similar to those presented for the Central North Sea and Outer Moray Firth, but detailed comparison is hampered by the lack of data presented along with the other frameworks.

This work differentiates the Maureen sequence from the overlying arenaceous deposits, and describes the Maureen interval as a period of relatively low sedimentation, mainly resulting from sporadic redeposition of the basin margin into the basins. No significant accumulation is observed in the Northern North Sea before the Maureen sequence, in contrast to the preservation of Ekofisk Formation strata in the Central North Sea.

The Andrew / Lower Balmoral sequences represent the time of most significant sediment flux into the basin in the Paleocene. Two depocentres are documented, and the ambiguity of their relative timing is resolved. The older depocentre occurs in the Viking Graben, following which arenaceous sedimentation switches to the East Shetland Basin. The shift in locus of sedimentation is probably concomitant with retrogradational stacking of the deposits in the Viking Graben, and transgression of the Bressay High. Prior to this, no evidence of deposition or erosion is observed on the East Shetland Platform in the Bressay area, suggesting that the influx of sediment into the Viking Graben was not associated with incision of the platform. No evidence was observed of active intrabasinal tectonism during the Paleocene.

Base-level fall in the Forties sequence resulted in erosion in the Bressay area, and incision of the underlying Lower Balmoral sequence. The development of a nick-point in the platform in the block 3/28 area led to direct supply of the fluvial / shallow marine...
sediments into the Viking Graben. These are preserved as an unusually thick and clean sediment body in the block 3/29 area. The Forties sequence marks the period of maximum base-level drop in the Paleocene in the Northern North Sea, as in the Outer Moray Firth, but it is accompanied by relatively low accumulation of Forties age sediments.

Regression from the East Shetland Platform occurred again during the Sele sequence, resulting in re-incision and re-occupation of the Forties incised-valley in the Bressay area. In contrast to the underlying Forties sequence, sediment supply is believed to have been high, and a major progradation package (the Ninian delta) was fed along strike into the East Shetland Basin.

In the Bressay area, incision of the Forties / Sele sequence fluvial systems into the underlying, relatively uncompacted shales resulted in significant lateral differential compaction, which subsequently formed the Bressay discovery. In contrast, the 9/3 discovery was formed as changing drainage patterns (possibly caused by the uplift of the Bressay Granite) caused incision of the updip portion of a shelf sand body.

In the East Shetland Basin, progradation of the fluvial-dominated Ninian delta probably occurred in a lobate manner. The delta topsets may represent aggrading fluvial systems, coeval with the younger, most distal delta lobes. Abandonment of the delta occurred abruptly, probably by in-place drowning.

The changing character of the sequences in the basin imply that sediment supply factors were very influential in the development of the Paleocene of the Northern North Sea. The contrast between the Forties and Sele sequences indicates that the uplift of the basin margin was not coincident with sedimentation into the basin. Similarly, uplift during the Maureen sequence did not correspond with a large sediment flux into the basin. Once sediment reached the basin, the bathymetry of the platform edge was a strong control on sediment distribution.

The fluctuating sedimentation rates in the basin gave rise to the variable character of the preserved depositional sequences. This may have enhanced or retarded the development of both sequence boundaries and genetic sequence boundaries (condensed sections) in different parts of the basin. Caution is therefore required in correlating the dissimilar sequence characters across the basin.
Incision over the Bressay granite is coincident with a major change in igneous activity in the North Atlantic Igneous Province, and immediately prior to the inception of sea floor spreading in the Northeast Atlantic. It is therefore suggested that a change in the regional stress field at this time may have resulted in the local isostatic re-equilibration of the Bressay Granite, which in turn enhanced contemporaneous incision in the Bressay area.

**6.9 Recommendations for future research**

This work has produced a number of conclusions, the implications of which could not be fully pursued here. They thus form the basis of some recommendations future work, as outlined below.

The stratigraphic framework devised here could be usefully extended in terms of the geographic coverage of the wells. The good biostratigraphy used in this study mainly came from the southern East Shetland Basin, and so the differentiation of the Forties / Sele sequences in the more basinal locations was uncertain. A larger database would also improve the resolution of the sequences, which would more clearly distinguish the Andrew / Lower Balmoral sequences.

The collection of good biostratigraphic data is vital for improving the resolution of the Paleocene stratigraphy in the East Shetland Basin. Although the data contained herein was of good quality by most company standards, it still lacked resolution, particularly in the most uncertain stratigraphic sections (the Forties, Sele and Balder intervals).

The geographic variation of Paleocene sedimentation is still poorly documented, within the Northern North Sea (especially the Quad 9 area), but also compared to the Outer Moray Firth and the West of Shetlands. Further integration of these areas would refine our understanding of the Scotland / Shetland / Orkney uplift. However before this could be undertaken, the differences between the published frameworks need to be more clearly understood.

A particular strength of this research is the inclusion of some East Shetland Platform data, which gave a clear insight into the controls on the basinal evolution. Extension of this aspect of the work could be usefully undertaken using high resolution 2D regional seismic (e.g. the Hex-88 survey), and 3D seismic data. The existence of a few platform wells (e.g. the recent Chevron well 8/4-1) would help substantiate this work.
3D seismic data is a very powerful tool, and more importantly, it is slowly becoming available for academic study. Much of the work unravelling the details of Paleocene depositional processes came from 3D seismic data in this study. The extension of this, particularly in the basin margin areas could produce some important results, as exemplified by the work of Milton & Dyce (in press).

Another facet of this work which was not evolved was a full consideration of sequence stratigraphy (stratigraphic correlation) in basinal settings. This could be significantly improved with spectral gamma ray studies (as touched on here), and given the paucity of biostratigraphic data, perhaps also the application of geochemical correlation techniques. The application of such techniques might allow the underlying sediment trends to be identified, and make the interpretation of maximum flooding surfaces / condensed sections more viable. This would however probably require access to sidewall cores.

Given the general lack of core data in the Paleocene of the North Sea (compared with the Jurassic, for instance), a higher density of sidewall cores with more precise descriptions would considerably improve the available resolution of the Paleocene.

The possible role of the Bressay Granite in enhancing uplift is an intriguing result. There are no granite bodies in similar positions at the edge of the East Shetland Platform, but the effect could have extending to basinal granite bodies (e.g. in the Outer Moray Firth), and the observation that isostatic re-equilibration may have taken place due to a change in the regional stress patterns has other implications. For instance, was the regional stress change sufficient to release previously locked faults? If so, limited movement of locked faults could have caused the subtle traps at the graben margin where differential compaction could have been inhibited.

Two mechanisms to produce stratigraphic traps are observed in the Bressay area: differential compaction due to the incision of fluvial systems into an underlying semi-compacted offshore shale succession, and the incision of a shelf-margin wedge due to drainage pattern changes during falling base-level. The seal in both cases is the pervasive Balder sequence, which is present everywhere in the North Sea. The fact that the prospects are relatively shallow may have enhanced prospectivity, as deeper in the basin, the Balder sequence is pervasively faulted in the basin due to overpressuring. It is reasonable to assume that similar plays have resulted from fluvial incision elsewhere on the East Shetland Platform, and the area is considered under-explored.
References


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Dixon, R. J., & Pearce, J., In press. Tertiary sequence stratigraphy and prospect evaluation, Bruce-Beryl Embayment, Quadrant 9, Viking Graben, UKCS. Stratigraphy of North West Europe, Norwegian Petroleum Directorate, Stavanger.


Green, P. F., 1989. Thermal and tectonic history of the East Midlands shelf (onshore UK) and surrounding regions assessed by apatite fission track analysis. J. Geol. Soc. Lon. 146, 755-773


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Appendix A

Biostratigraphic Markers

Principal Biostratigraphic Markers Used in this Study

The data listed here was principally complied from biostratigraphic reports (particularly Simon Robertson and Paleo Services reports), and cross referred principally to a number of stratigraphic publications (Neal, 1994; Neal et. al., 1994; Mudge & Copstake, 1992a,b; Mudge & Bujak, 1994, etc.) as noted in chapter 2.

The shorthands M1 to M7 and P1 to P3 refer to bioevents of Mudge & Copstake (1992a, b). Bioevent M2 is marked by the following taxa: G.cf.co., G. in., E.tr., G.ps., G. tr. & G. co..

Palynomorphs

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<th>Name</th>
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<td>A. augustum FDO</td>
<td></td>
</tr>
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<td>A. augustum -Acme = A. spp. Amce (UKOOA)</td>
<td>P3</td>
</tr>
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<td>A.gi.</td>
<td>A. gippingensis FDO</td>
<td></td>
</tr>
<tr>
<td>A.gi.-A</td>
<td>A. gippingensis -Acme</td>
<td></td>
</tr>
<tr>
<td>A.H-C</td>
<td>A. sp.2 (Heilman-Clausen, 1985)</td>
<td></td>
</tr>
<tr>
<td>A.ma.</td>
<td>A. margarita FDO = A.gi. FDO (UKOOA)</td>
<td>P2</td>
</tr>
<tr>
<td>A.re.</td>
<td>A. reticulata FDO = Spiniferites FDO</td>
<td></td>
</tr>
<tr>
<td>A.spp.</td>
<td>A. spp. Acme</td>
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</tr>
<tr>
<td>A.su.</td>
<td>A. summisum FDO</td>
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</tr>
<tr>
<td>C.ed.</td>
<td>C. edwardsii FDO</td>
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</tr>
<tr>
<td>C.sp.</td>
<td>C. speciosa FDO</td>
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</tr>
<tr>
<td>C.wa.-A</td>
<td>C. wardenense -Acme</td>
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<td>D.co.</td>
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<td>D.oe.</td>
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<td>D. oebisfeldensis -Acme</td>
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<td>Inaperturopollenites -Acme</td>
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<td>L.L.</td>
<td>Large Leiospheres FDO</td>
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</tr>
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**Microfossils**

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<td>Cenodiscus -Acme</td>
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<td>E. trivialis FDO</td>
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<td>G. aff. trivialis sensu Blow 1979 FDO</td>
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<td>T.ru.</td>
<td>T. ruthvenmurrayi FDO</td>
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Appendix B

Velocity Modelling

Method

The following steps were taken to build a simple model to mimic the pull-up and compaction patterns observed on seismic in the Bressay area.

a) Porosities were calculated to estimate present compaction of S1 and Sh1, and compaction of the Andrew shale (AndSh) at time of sand deposition (702' + (0.5*301') = 852' depth). Original porosities were obtained from Baldwin & Butler (1985)

b) Bulk velocities were calculated and cross-checked against the seismic section (±2% variation)

c) Shale thicknesses were set constant, as measured in well 3/27-1

d) Sand thickness was the variable

e) Shale thicknesses were calculated following incision of sand

f) The individual units were compacted using compaction factors, scaled for the
% sand content

g) The velocity of the compacted units was calculated, with velocities scaled for
% sand content

h) The model values were plotted, using the base Andrew shale as a datum for
compaction, and the top sand as a datum for compaction.

i) The modelled compaction and pull-up were compared with the measured
seismic section, and starting parameters were varied to try and obtain a best fit.
Assumptions

Porosities: Sand
Original 35% (estimate, from B&B)
Present 27% (sonic log)

Porosities: Shale 1
Original 70% (estimate, P. Farfan pers. comm.)
Present 22% (estimated from Shlumberger chart from sonic log)

Porosities: Lower Balmoral Shale
Original 40% (estimate, from B&B at 260m burial depth)
Present 22% (estimated from Shlumberger chart from sonic log)

Velocities
Sand 9100 feet/sec (from sonic log)
Shale 1 7440 feet/sec (from sonic log)
Andrew Shale 7340 feet/sec (from sonic log)
Eocene Shale 7340 feet/sec (estimate)

Notes
Bulk velocities and compactions for units worked out as ratios of percentage sand and shale content.

The model used the same shale velocities and compaction across the model. Thus for a calculated sand content of 20% outside mound, the shale velocities and compaction inside the mound (averaged for a composition of 20% sand, 80% shale) varied by 4% from "sand content of central mound = 80%; Sand content outside mound = 20%". This applies in all examples.

Well 3/27-1 Data

Total thickness 1003'
Shale 1 thickness 702'
Andrew Shale thickness 301'
Pull-up (line Sov-812-37) 38ms
Compaction (line Sov-812-37) 73ms

Sample data

Present sand porosity 27%, Eocene shale velocity 8000 feet / sec

A: Sand content of central mound = 100%; Sand content outside mound = 0%

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<th>Compaction (ms)</th>
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<td>20.5</td>
<td>75.9</td>
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<tr>
<td>700</td>
<td>23.9</td>
<td>88.5</td>
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<tr>
<td>800</td>
<td>28.3</td>
<td>91.7</td>
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<tr>
<td>900</td>
<td>32.7</td>
<td>94.8</td>
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B: Sand content of central mound = 80%; Sand content outside mound = 0%

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<td>900</td>
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C: Sand content of central mound = 80%; Sand content outside mound = 20%

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<tr>
<td>900</td>
<td>21.5</td>
<td>54.3</td>
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Present sand porosity 27%, Eocene shale velocity 7600 feet/second

D: Sand content of central mound = 80%; Sand content outside mound = 0%

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E: Sand content of central mound = 80%; Sand content outside mound = 20%

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<tr>
<td>900</td>
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<td>57.1</td>
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Present sand porosity 25%, Eocene shale velocity 7600 feet/second

F: Sand content of central mound = 80%; Sand content outside mound = 0%

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G: Sand content of central mound = 80%; Sand content outside mound = 20%

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Present sand porosity 23%, Eocene shale velocity 7600 feet/sec

H: Sand content of central mound = 80%; Sand content outside mound = 0%

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Present sand porosity 25%, Eocene shale velocity 7600 feet/sec

Sand Velocity increased from 9100 feet/sec to 9600 feet/sec

I: Sand content of central mound = 80%; Sand content outside mound = 0%

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</tbody>
</table>
Appendix C

Listing of Well Picks

The following list gives the measured depths of the picks indicated in the figures in this thesis. They are representative of the Paleocene in the northern North Sea.

The picks have two errors associated with them: sampling errors (+/- 30ft), and ambiguities in interpretation (in the order of +/- 10ft). The depths listed should here should be taken as superceding the diagrams: any small differences between the figures and this data is due to errors introduced in drafting.

<table>
<thead>
<tr>
<th>Well</th>
<th>Base Pal</th>
<th>Top Pal</th>
<th>Top Maur</th>
<th>Top Lower Balm</th>
<th>Top Upper Balm</th>
<th>Top Forties</th>
<th>Top Sele</th>
<th>Top Balder</th>
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Enclosure 2. (a) A relative sea-level curve constructed for the Paleogene of the Outer Moray Firth, and (b) a line drawing of the interpreted seismic geometries used to derive the relative sea-level curve. Two long-duration relative sea-level cycles are represented. The total fall of relative sea-level in the Late Paleocene was in the order of 800m, followed by a rise of 500m. From Jones & Milton (1994). See Enclosure 3 for correlation of sequences.
Enclosure 3. Biostratigraphic correlation of selected sequence stratigraphic and lithostratigraphic schemes and that of this study. See Appendix A for biostratigraphic codes.
Enclosure 4. Best-fit Graphic Correlation of wells in the thesis. The plot shows lines of correlation (LOCs) honouring the individual data points. The LOCs represent uncompacted sedimentation rates for each well. See section 2.7 for discussion.
Enclosure 6. Graphic correlation of wells 9/3-1 (East Shetland Platform) and 9/4-1 (Viking Graben). The data indicates that the thick sand succession in well 9/4-1 is partly of Andrew sequence age. Note that deposition starts in well 9/3-1 during the Lower Balmoral sequence. The interpretation of well 9/4-1 is contrasted with the lithostratigraphic interpretation of Knox & Holloway (1992).

Sequence abbreviations: B: Balder; S: Sele; 40s: Forties; U.B.: Upper Balmoral

Sequence abbreviations: B: Balder; L: Lower; S: Sele; 40s: Forties; U.B.: Upper Balmoral

Knox & Holloway (1992)
Enclosure 7. Line NNSTI-88-022 over the 9/3 discovery. The boundary of the Forties and Sele seismic sequences can not be traced all the way to the west, but incision at the base of the Sele seismic sequence is thought to continue updip. Compare inset with Figure 5.7b for location.
Enclosure 8. Isopach (left hand side) and facies maps of the Andrew / Lower Balmoral sequences in the Greater Bressay area.
Enclosure 9. Top Balder to base Forties isochron (TWT)

Key

- 100ms
- 200ms
- 300ms

Contour interval 50ms

Thickened Forties & Sele interval allows sequences to be separated. Note sharp change in isochron thickness representing the offlap break of the Sele delta.

Outline of underlying Bressay Granite

N Viking Graben
Enclosure 10. Interpretation of seismic line ESBT89-208 running from the East Shetland Platform into the East Shetland Basin. See Enclosure 13 for location.
Enclosure 11. Correlation 5.6b running N-S down the centre of the East Shetland Basin, East of the Bressay High. All wells apart from 3/14-1 and 3/19-1 have biostratigraphic control. See Enclosure 13 for location.
Enclosure 12. Correlation 5.8 running W-E from the Bressay High into the North Viking Graben. See Enclosure 13 for location.
Enclosure 13. Location of regional well & seismic correlations in this study.
Enclosure 15. Correlation 5.2 running W-E through the northern East Shetland Basin. See Enclosure 13 for location.
Enclosure 16. Correlation 5.3 running N-S down the west of the East Shetland Basin. See Enclosure 13 for location.
Enclosure 17. Correlation 5.3b running N-S down the west of the East Shetland Basin onto the Bressay High. See Enclosure 13 for location.
Enclosure 20. Correlation 5.6 running N-S down the centre of the East Shetland Basin. See Enclosure 13 for location.
Enclosure 22. Seismic line tie between Ninian exploration wells. For orientation, see Figure 4.1b. Well logs plotted with time on vertical axis. Compare with Enclosure 23.
Enclosure 23. Correlation of wells 3/3-2, 3/3-7 and 3/3-8 in the Ninian field. Correlation of the 'topset' interval is not clear when both the 'topsets' and the top of the underlying delta-front are arenaceous. Correlation of the 'topsets' is here constrained using 3D seismic data, which shows a clear change from clinoforms (clinoform tops indicated by dashed lines in Forties / Sele sequence) to subhorizontal, subparallel 'topsets'. Well 3/3-2 is a type well for the Sele Formation as defined by Mudge & Copestake (1992b) (left hand column).
Enclosure 24. Seismic inline I450 & interpretation (see Figures 4.1b for location). The position of the Jurassic footwall crest is projected onto the interpreted section, and is not shown on seismic. Compare with version of same line in Enclosure 25 for clarity.
Enclosure 25. (a) Inline 400 illustrating the along-strike change in character of the progradation of the lobe 2 (younger, right) over lobe 1 (left). The boundary is marked in green (line = interpretation; circle = intersection of interpretation from another line). The younger lobe has clinoforms of slightly higher reflectivity, dipping at a steeper angle. Note the relatively steep depositional profile formed by offlap break of lobe 1, and the discontinuity of the lobe 1 clinoforms. The oldest reflectors in lobe 2 are mounded, and onlap lobe 1 almost horizontally. Depth of section shown is 1300ms to 2500ms. (b) Inline 450. Little evidence is observed of mounded reflectors onlapping the older lobe. Accommodation space above the feather edge of lobe 1 has allowed progradation of lobe 2 reflectors, but the exact relationship of these reflectors and those to the east is not clear - slope bypass may well of occurred at the intersection of the two sets of clinoforms. (c) Inline 500. (d) Inline 550. The lobe 2 clinoforms dominate the deltaic interval in this line. The black lines highlight the onlap of the base Andrew / Lower Balmoral sequence against the break in slope. See Figure 4.1b for orientation.
### Enclosure 26: Table 5.1
Seismic character of stratigraphic units on the Bressay High

<table>
<thead>
<tr>
<th>Unit</th>
<th>Stratigraphy</th>
<th>External morphology</th>
<th>Base reflector terminations</th>
<th>Top reflector terminations</th>
<th>Internal architecture</th>
<th>Seismic character</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lower and Upper Balmoral Sequences</td>
<td>Incised sheet, thickening to south</td>
<td>Subhorizontal. Very strong basal reflector (significant unconformity)</td>
<td>Sub-parallel to overlying / low angle toplap. Erosional truncation where incised.</td>
<td>Occasional internal onlap</td>
<td>Low amplitude to transparent reflectors. Low to moderate continuity interspersed with more chaotic areas</td>
<td>Shelfal shale sequence deposited at relative highstand</td>
</tr>
<tr>
<td>2</td>
<td>Forties and Sele Sequences</td>
<td>Mounded and incising sheet</td>
<td>Downlap to East. Onlap against incised valley margins.</td>
<td>Sub-parallel / low angle toplap</td>
<td>Internal downlap and bidirectional downlap. More chaotic internal to mounds</td>
<td>Moderate to high amplitude. Low continuity.</td>
<td>Multiple delta progradation in incision</td>
</tr>
<tr>
<td>3</td>
<td>Balder Sequence</td>
<td>Sheet, draping underlying</td>
<td>Onlap to West</td>
<td>Downlap, occasional onlap against Sele / 40s mounds</td>
<td>Occasional downlap and onlap</td>
<td>Moderate amplitude. Low to high continuity.</td>
<td>Transgression associated with opening of Atlantic to NW</td>
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Enclosure 27: Table 5.2
Seismic character of stratigraphic units at the margin of the Bressay High (3/28b-3 area)

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<th>Unit</th>
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<th>External morphology</th>
<th>Base reflector terminations</th>
<th>Top reflector terminations</th>
<th>Internal architecture</th>
<th>Seismic character</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Andrew &amp; Lower Balmoral Sequences</td>
<td>Basinward-thickening wedge</td>
<td>Onlap to West against ESP</td>
<td>Sub-parallel: no visible terminations</td>
<td>Occasional internal onlap</td>
<td>Moderate reflector amplitude &amp; continuity</td>
<td>Fan apron onlapping ESP deposited at relative lowstand</td>
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</tr>
<tr>
<td>2</td>
<td>Upper Balmoral Sequence</td>
<td>Basinward-thickening wedge</td>
<td>Onlap against ESP in lower part. Downlap onto ESP in upper. Downlap onto Andrew sequence distally</td>
<td>Sub-parallel to overlying.</td>
<td>Complex internal onlap and downlap downdip. Sub-parallel updip.</td>
<td>Moderate reflector amplitude &amp; continuity, varying significantly vertically and laterally</td>
<td>Fan apron onlapping and then transgressing East Shetland Platform</td>
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<tr>
<td>3</td>
<td>Forties Sequence</td>
<td>Sheet</td>
<td>Onlap against ESP in Viking Graben. Downlap over ESP.</td>
<td>Sub-parallel: no visible terminations</td>
<td>Occasional internal onlap or downlap</td>
<td>Moderate to high reflector amplitude. Variable continuity.</td>
<td>Distal deposits of prograding shelf. (Sediment bypass to south)</td>
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<tr>
<td>4</td>
<td>Sele Sequence</td>
<td>Lens</td>
<td>Downlap to North and East</td>
<td>Toplap</td>
<td>Internal downlap</td>
<td>Moderate amplitude. Low continuity.</td>
<td>&quot;Perched&quot; shelf-edge delta, fed along strike</td>
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<tr>
<td>5</td>
<td>Balder Sequence</td>
<td>Sheet, draping underlying</td>
<td>Onlap against Sele highs</td>
<td>No visible termination</td>
<td>Occasional downlap</td>
<td>Low to high amplitude. Moderate to high continuity.</td>
<td>Transgression associated with opening of Atlantic to NW</td>
</tr>
</tbody>
</table>
Enclosure 28. Seismic line UK85-112. Dip line extending from the Alwyn Slope in the southwest (left hand side) into the southern East Shetland Basin. The Figure illustrates the lens-shaped cross section of the Forties and Sele sequences on the Alwyn Slope. Updip, the Forties / Sele interval is observed to thin significantly, which could possibly be due to erosion, but no direct evidence of reflector termination was observed, and there was no well control in this area. Lower down, the Andrew / Lower Balmoral sequences onlap the platform margin, finally transgressing onto the Bressay area in the upper part of the Lower Balmoral sequence. Horizons: Base incision = top Upper Balmoral = dark green; Top Balder = black; Top Sele = dark blue; base Paleocene = lighter green. Horizontal lines are 500ms apart. Width of display approximately 10kms.
Enclosure 29. Bressay well correlation illustrating different possible episodes of incision. Datum on base Paleocene. Sequence names at RHS. See Figure 5.1 for well locations.
Enclosure 30. Composite contour map of the top Upper Balmoral horizon traced from the north and south Ninian 3D surveys. Compare with Figures 4.7 and 4.8. Notice the change in contour interval between surveys.
Enclosure 31. Composite contour map of the top Balder horizon traced from the north and south Ninian 3D surveys.
Enclosure 32. Contour maps as figures in chapter 5, annotated with well locations and block boundaries. (a) Top Balder two way time (TWT), (b) base Upper Balmoral TWT, (c) base Paleocene TWT. All contour intervals 20ms. Block and well names annotated in (a). Outline of the Bressay field dotted in lower LH corner of each diagram.
Enclosure 33. Contour maps as figures in chapter 5, annotated with well locations and block boundaries. (a) Top Balder to base Upper Balmoral isochron, (b) base Upper Balmoral to base Paleocene isochron. Contour intervals 20ms. Block and well names annotated in (a). Outline of the Bressay field dotted in lower LH corner of each diagram.