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A stratigraphic analysis of Paleogene deposition in Northwest Europe and the role of graphic correlation in sequence stratigraphy

Neal, John Edward, Ph.D.
Rice University, 1994
RICE UNIVERSITY

A STRATIGRAPHIC ANALYSIS OF PALEogene DEPOSITION IN NORTHWEST EUROPE AND THE ROLE OF GRAPHIC CORRELATION IN SEQUENCE STRATIGRAPHY

by

JOHN EDWARD NEAL

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE DOCTOR OF PHILOSOPHY

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ABSTRACT

A Stratigraphic Analysis of Paleogene Deposition in Northwest Europe and the Role of Graphic Correlation in Sequence Stratigraphy

by

John Edward Neal

A sequence stratigraphic analysis of Paleogene deposits, using subsurface data (well logs, seismic data, and biostratigraphy) from the Central North Sea and published outcrop information from northwest Europe, has documented a framework of 30 “third order” depositional sequences nested within 5 “second order” major regression/ transgression cycles. The order of a cycle is based on observations concerning its constituents and its impact on the depositional systems of the basin, not strictly on its duration.

Integration of composite standard biostratigraphy with sequence stratigraphy builds a consistent chronostratigraphic depositional framework. The framework is based on the identification of hialtal intervals in wells, boreholes, and outcrop using graphic correlation. Hialtal interval is a generic term that differs from condensed section. Discontinuous sedimentation is assumed of across some units traditionally called “condensed sections”. This assumption is based on evidence from regional correlation of graphic correlation terraces. An ideal relationship of graphic correlation terraces within a sequence stratigraphic model is presented, providing the theoretical basis for regional correlations. Weaknesses in graphic correlation (underuse and static application) are
countered with strengths in sequence stratigraphy (widespread use and dynamic application). Conversely, weaknesses in sequence stratigraphy (documentation and consistency) are the strengths of graphic correlation. This study emphasizes the interdependence of the two methodologies.

A depositional model is also proposed as a variant of the classic Vall model. This model considers the effect of depositional profile and sediment supply in the preservation and distribution of systems tracts. Recent revisions in Central North Sea lithostratigraphy and sequence stratigraphy provide an opportunity for comparison between different methods and data resolutions. The stratigraphic framework built from subsurface data is compared with age-equivalent deposits outcropping in Northwest Europe. This correlation reveals that sedimentation in the deep basin occurs as depositional pulses, separated by time-correlative graphic correlation terraces (hiatal intervals). Data terraces expand into thick deposits in Northwest Europe. Not all sequence boundaries are resolvable by graphic correlation, but the method brackets packages defined by seismic, log interpretation and biostratigraphy. By correlating outcrops and subsurface data, it is possible to construct a relative sea level signal for the entire basin.
Acknowledgments

This thesis is the product of work done at Rice University, Amoco (U.K.) Exploration in London, and Ecole des Mines in Paris. Debts of gratitude are owed to many people who made this study possible, but none as great as that owed to my advisor, Professor Dr. Peter R. Vail. By treating me as an equal from my first day at Rice to stimulating discussion and being supportive throughout this study, Dr. Vail has given me unparalleled opportunities and I am proud to have worked for him and to call him a friend. I am also deeply grateful to Amoco paleontologists, Jeff Stein and Jim Gamber, whose help and discussion made it possible to understand and use graphic correlation. Their open-mindedness and expertise helped me grapple with correlation problems and understand fundamental biostratigraphic concepts. Thanks guys, I could not have done it without you! I am also grateful to my committee, André Droxler, John Oldow, Dale Sawyer, and Rich Smith for taking the time to critique my work and improve my presentation and understanding.

I thank Amoco Production Co. for funding throughout this study, especially Art Berman, who found ways to provide me with support during difficult times. I also thank Cande Krebs at Amoco for first approaching me with the offer to support my research. I am indebted to Amoco (U.K.) Exploration Co. for providing me with office space and logistical support during my stay in London, especially George Chisholm and Dave Walker. I also thank the scientists at Amoco (U.K.) for their help and discussion, especially Tim Berg, Steve O'Connor and Dick White.

I am grateful to Professor P. Ch. de Graciansky for hosting us at Ecole des Mines while working on the European Basins project and for providing travel
support to talk to various experts around Europe. À Pierre Charles, je vous remercie pour tous vos aides. J’ai passé un bon sejour à Paris. I appreciate the help of stratigraphic experts in Europe for their time and input to this work, especially Prof. Noël Vandenberghe, Dr. Robert Knox, Dr. Claus Heilmann-Clausen, Dr. Janine Riveline, and many others who have provided stimulating discussions at conferences. I thank you all for your help and hope you are pleased with the result.

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I am very grateful to technical companies that allowed me access to and publication of selected portions of a great data base. Simon Petroleum Technologies (Robertson Research and Horizon Geophysical ) has been helpful throughout, kindly allowing me to publish key biostratigraphic and seismic data. The same is true of GECO-Prakla and Nopec, who allowed me to publish key regional seismic lines.

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This thesis, although no Beethoven sonata, is done for Elise.
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Preface

This thesis is a combination of papers submitted to journals and special publications and, therefore, much of the content in chapters 2-4 overlaps. The integration of the graphic correlation technique and sequence stratigraphy is a new approach and extensive methodology explanations are necessary for each chapter to stand alone as professional papers. Chapters 2 and 4 were co-authored with Amoco paleontologists, Jeff Stein and Jim Gamber. Chapter 3 was co-authored with Stein, Gamber, and Peter Vail. Chapter 4 is accepted to the Journal of Micropaleontology and will be appearing in print in the summer of 1994. Chapter 2 is an invited paper to a SEPM research conference on sequence stratigraphy. It will appear in a special publication to be out in December, 1994. Chapter 3 has an uncertain fate at present as it could appear in a Geologic Society of London special publication on Early Paleogene correlations in Northwest Europe and/or the SEPM volume of Mesozoic/Cenozoic Sequence Stratigraphy for European Basins. Chapters 2 and 3 are currently in review.

Much of the data used to construct the composite standard biostratigraphy could not be published since it is the property of Simon Petroleum Technologies (Robertson Research). The composite standard was built mainly from biostratigraphic well reports in Robertson Research’s Central Graben (1987) and South Viking Graben (1989) Paleocene-Eocene studies. S.P.T. kindly allowed me to publish the complete data of a key reference well, N16/1-1, which is shown in chapter 3 and Appendix Table 1. Hopefully this information, combined with graphs of published borehole and outcrop data will allow this work to be reproduced independently.
Seismic lines used in this study are also proprietary data, but, thanks to GECO-Prakla, Nopec, and S.P.T. (Horizon Geophysical), I can published key sections in interpreted and uninterpreted form. The seismic grids used for correlations are CNST 82- (02-06, 11-17) and 86- (13.5-14.5, 28-34) grids of GECO-Prakla and Nopec, and the HEX 88- (6-16, 51-59) grid of Horizon Geophysics. Amoco Production Co. and Amoco (U.K.) Exploration Co. allowed me access to these lines with computer support to produce synthetic seismograms with Sierra® software.
Chapter 1

Introduction to the Study: Objectives and Implications

The objective of this research project was originally to test the concept of eustasy by comparing a detailed sequence stratigraphic framework, built from Central North Sea subsurface data, to similar frameworks published for the Paleogene in the U.S. Gulf Coast. It soon became clear that this goal was unobtainable unless a study of the same detail was conducted on Gulf Coast data. It was decided that detailed documentation of Central North Sea sequence stratigraphy, correlated to a wealth of information published on similar aged section outcropping in northwest Europe would provide a good start on the process of testing eustasy. Detailed stratigraphic research in other Paleogene basins will have the documented model of this study for comparison.

Documentation of stratigraphic cycles observed in seismic, well and outcrop data was provided by integration of the composite standard method of biostratigraphy (Shaw, 1964). A model was developed to relate biostratigraphic data “terraces” to a sequence stratigraphic model. The graphic correlation of biostratigraphy from a single well or outcrop section with an ideal complete, or composite standard section allows the recognition of stratigraphic gaps. These gaps can be matched with terraces in data from other sections to demonstrate the chronostratigraphic equivalence of section between terraces that overlap in time. This principle is the basis of depositional sequence correlations made in the subsurface, tied to onshore outcrops and boreholes.

The main goal of this thesis is to provide a documented and reproducible stratigraphic framework of depositional cycles. This thesis contains original
interpretations of data acquired for hydrocarbon exploration in the Central North Sea. The data is either open file (well logs) or contained within contractor surveys with multiple clients. Several wells and seismic lines used in the following chapters have been published with different interpretations by other authors. Many of the wells appear in the revised Paleogene lithostratigraphy, published recently by the British Geological Society (Knox and Holloway, 1992). Seismic data was made available to me by the contractors who own the rights to them. I found that access to this data was easily obtained for persons interested in testing the conclusions reached by this study. With the release of well information from N16/1-1 and a comparison of published borehole reports that are graphed in the following chapters, it is hoped that future researchers will be able to reconstruct the composite standard that provided the basis for the correlations presented here.

A further goal of this work is to achieve some level of agreement in the recognition of cycles by previous authors for this stratigraphy. This goal requires a synthesis of large volumes of published biostratigraphic, lithostratigraphic, and depositional environment data, as well as discussion with the various stratigraphers with expertise in each section. As coordinator for the Paleogene section of the Mesozoic/Cenozoic Sequence Stratigraphy of European Basins Project, I had the opportunity to discuss correlations with many experts and develop a synthesis that is contained in the chronostratigraphic summary charts in following chapters. Any differences in my interpretation of these correlations with those published by individual authors represents conclusions that were reached from the synthesis of the stratigraphy from all basins studied and local exceptions are likely.
A third goal of this study has implications for correlation to other basins and stratigraphy in general. This is an understanding of the limitations, strengths, and utility of graphic correlation in sequence stratigraphic analysis of a basin. Evaluation of the potential advantages and pitfalls of this integration required research into not only the methods themselves, but also the completeness of the stratigraphic record and biostratigraphy's ability to resolve any complications. This problem has led to a recognition of nested stratigraphic cycles and a documentation of section expanded in shelfal areas that is hialtal in deep parts of the basin. The fractal nature of geology ensures that all stratigraphic cycles will not be resolved with the limited biostratigraphic tools available, but biostratigraphy can document the correlation of as many cycles as permitted by resolution. Northwest Europe has excellent biostratigraphic information for the Paleogene and can serve as a model for areas with less precise resolution until another area is studied in more detail to improve on the resolution presented in this study.
Chapter 2
Integration of the Graphic Correlation Methodology in a Sequence Stratigraphic Study: Examples from the North Sea Paleogene

Chapter Summary
The composite standard method of biostratigraphy, described by Shaw (1964), provides a consistent temporal framework for stratigraphic analysis of a basin. The method graphically correlates the stratigraphic succession of an individual section relative to an ideal composite section. Sequence stratigraphy provides a genetic correlation of deposits in different depositional settings based on physical surfaces in the rock record and a 2-D model that relates deposits in a dip profile to changes in relative sea level. Weaknesses in graphic correlation (underuse and static application) match well with strengths in sequence stratigraphy (widespread use and dynamic application). Weaknesses in sequence stratigraphy (documentation and consistency) can be equally well matched with the strengths of graphic correlation. The integration of these two stratigraphic methodologies can be a powerful tool in basin analysis as long as both techniques are applied correctly and the data limitation and interpretation complications are known.

Introduction
Since its development in the early 60’s (Shaw, 1964), the practical utility of the graphic correlation methodology has been largely overlooked by the geologic community. Meanwhile, chronostratigraphic representation of the rock record (Wheeler, 1958) and its division into cratonic sequences of transgression and regression (Sloss, 1963) gained popularity. Seismic stratigraphy (Payton, 1977), then sequence stratigraphy (Wilgus et al., 1988),
developed from the work of Sloss and Wheeler and captured the imagination of geologists and geophysicists worldwide. The integration of graphic correlation with sequence stratigraphy has the potential to produce a documented and consistent chronostratigraphic depositional framework.

Sequence stratigraphy seeks to subdivide the rock record into depositional sequences, which are defined as "a stratigraphic unit composed of a relatively conformable succession of genetically related strata bounded at its top and base by unconformities and their correlative conformities" (Mitchum et al., 1977). Depositional sequences are hypothesized to result from changes in relative sea level, which is a combination of tectonic subsidence and eustasy. One of the most controversial aspects of sequence stratigraphy has been the demonstration of time equivalence of events, which requires documentation not published with the eustatic curves of Exxon (Haq et al., 1988). The concept of eustasy has been controversial since its inception, and remains so today for periods of geologic history that do not have the proven glacio-eustatic fluctuations of the Plio-Pleistocene. Graphic correlation has the potential to test eustasy as was demonstrated by Prell et al. (1986), when they corrected $\delta^{18}$O records from 13 piston cores around the world using graphic correlation. The composite standard methodology can include all types of chronological data (biostratigraphic, magnetostratigraphic, isotopic, etc.) to produce a consistent temporal framework, with which different well or outcrop sections may be tested.

Much of the previously published work using graphic correlation has utilized relatively continuous lines of correlation (LOC), with few "terraces" (Edwards, 1984; 1989; Prell et al., 1986; Hazel et al., 1984). Terraces in the LOC represent section missing from the well or outcrop being graphed against the composite standard section (Shaw, 1964; Miller, 1977). Shaw and Miller point out that
LOC terraces can result from erosion, nondeposition, or section omission by faulting. There is much evidence to suggest that the stratigraphic record contains numerous gaps in the marine as well as nonmarine setting (Aubry, 1991; Sadler, 1981; Plotnick, 1986), gaps that graphic correlation has the potential to identify and equate (Harper and Crowley, 1985). Graphic correlation can identify stratigraphic gaps that overlap in time for multiple sections in different settings because it provides a consistent biostratigraphy. Overlapping stratigraphic gaps bracket chronostratigraphic units similar to the way sequence boundaries bracket depositional sequences. Demonstration of overlapping stratigraphic gaps in widely separated basins is a condition required but insufficient to prove global eustasy (Aubry, 1991). The relationship of graphic correlation terraces to sequence stratigraphic key bounding surfaces has the potential to provide the documentation sequence stratigraphy needs and the recognition that graphic correlation deserves. The difficulty remains in proper application of both techniques and a recognition of possible pitfalls in their integration.

Graphic correlation is best used in areas where outcrop or continuous core data allow the identification of faunal first appearance datums (FAD) as well as last appearances datums (LAD) or first downhole occurrences (top or FDO). This control adds an extra level of confidence in the interpreted LOC by capturing the full range of any particular taxa as originally proposed by Shaw (1964). Unfortunately, in the oil industry, economic necessity usually precludes the drilling of continuously cored wells. This fact requires that a different approach be used if graphic correlation is to be successful. In most cases, the geologist is fortunate to have a series of reported faunal tops, usually at 30 ft or 10 m cutting sample intervals, to construct a chronostratigraphic framework. Key
bounding surfaces (unconformities, transgressive surfaces, etc.) observed in wells, outcrop and seismic data are correlated within a temporal framework to suggest a paleogeographic and depositional model. Surface (or interval) - based stratigraphy, correlated with biostratigraphy and interpreted in terms of relative sea level fluctuations, is the essence of sequence stratigraphy.

**Graphic Correlation Terraces in a Sequence Stratigraphic Model**

The sequence stratigraphic model of Vall (1987) proposes a way to subdivide a sedimentary section based on seismic stratal patterns and well log interpretation as they relate to relative changes in sea level. This model was refined in Posamentier et al. (1988) and Posamentier and Vail (1988) to explain deposits observed along a given depositional profile through time. Deposition was modeled as a function of changing accommodation space (both on the shelf and onshore) and the response of depositional systems to fill that space. Van Wagoner et al. (1990) applied this model at outcrop scale, employing parasequence stacking patterns as a substitute for seismic scale geometries.

In a marine siliciclastic margin with a shelf-slope break, changes in accommodation space on the shelf control deposition in a dip direction (figure 2.1). Changes in shelfal accommodation space are caused by relative changes of sea level (relation of the sea surface to the inherited depositional profile-usually the previous sequence boundary). Relative sea level change is a function of subsidence (or uplift) and eustasy. The rate of sediment delivered to the basin (flux) determines how much shelfal accommodation space is filled. If sediment flux is greater than the rate accommodation space is created, the depositional system will prograde. Sediment bypasses to the deep basin if no shelfal accommodation space exists (and the profile is too steep for normal progradation) or if shelfal marine processes sweep sediment to the slope.
Figure 2.1. Brief overview of sequence stratigraphic concepts, showing how relative sea level is a function of subsidence and eustasy, how changes in relative sea level create shelfal accommodation space, and how changes in shelfal accommodation space create stratal patterns (systems tracts) as sediment flux interacts with the rate of relative rise through time.
(Posamentier et al., 1991). Unfilled accommodation space is equal to water depth in marine settings. At any given time, a depositional margin will possess some morphology that can range from steeply dipping escarpments to gentle ramps. This morphology is referred to as the depositional profile. The rate of change in shelfal accommodation space is directly linked to the depositional profile, controlling the styles of sediment fill (systems tracts) as relative sea level changes.

This model is so robust that it is common for sequence stratigraphic studies to all but ignore biostratigraphy (e.g. Van Wagoner et al., 1990) due to the power of the method and the ability to correlate log and outcrop markers over significant distances. While this approach may be applicable for continuous outcrop sections and field studies with very dense well control, it is a questionable practice when attempting regional studies with scattered subsurface or discontinuous outcrop data. Regional studies need a rigorous chronostratigraphy as the framework that allows a more detailed infilling of stratigraphic data at a later stage. This is the key contribution graphic correlation and a composite standard make to regional sequence stratigraphic studies.

**Construction of the composite standard**

A key advantage of a composite standard approach is that large amounts of data are effectively managed with all fossil groups (as well as other key chronological markers) placed in an ideal sequence. It improves the consistency of age correlations and provides a means of detecting and measuring stratigraphic hiatuses. It does, however, require a good knowledge of the expected fossil succession to identify reliable picks and note those subject to reworking or environmental limitations. The method will aid a stratigrapher in the interpretation of a section, but it will not identify key surfaces
in the well, nor can it distinguish unconformities (subaqueous or subaerial) from section removed by faulting. These interpretations must be made by the geologist.

When developing a composite stratigraphic standard for a basin, it is important to search the data set and available literature for a well or outcrop section with the most complete biostratigraphy, which serves as the initial reference section. Building the composite standard requires the incorporation of other wells representing the full range of paleogeographic locations in the basin. This step insures the capture of the most possible depocenters and, therefore, results in a more comprehensive composite standard database. As additional wells are added, the chronostratigraphic range of each fossil will become more fully expressed within the composite (Shaw, 1964; Edwards, 1984; Stein et al., in press). Interpretation of wells using a stabilized or mature database begins to provide real insight into depositional trends and basinwide events.

Before discussing applications, a brief explanation is necessary for the way graphic correlation is performed in a basin where the primary data source is ditch cutting samples. Using cuttings exclusively effectively removes half of the potential data base since FADs are likely to be untrustworthy markers due to the common problem of caving younger fossils into older samples downhole. Cavings cause a reported base (FAD) to be older than its correct stratigraphic position. For consistency, tops (LAD or FDO) and acme (most abundant) occurrences are the best markers in cuttings. The problem of reworked occurrences is lessened by making multiple passes through the data to stabilize composite ranges (Stein et al., in press). A stable composite standard is essentially a chronostratigraphic range chart (figure 2.2) where all fossil tops
**Fig. 2.2.** Diagramatic example of the graphic correlation procedure and interpretation. Lithology key: □ = sand, □□□ = silt, □□□□ = shale. Composite Standard Units have a linear scale for this example only (see text for further explanation).
and acme occurrences are assigned a value in composite standard units (CSU) that indicates the marker's position within the overall chronological sequence of fossil datums. Using the stable composite standard, a new well can be graphed to identify any missing or condensed intervals.

*Application and theory*

Graphic correlation interpretations start by plotting reported fossil tops by depth occurrence (vertical axis) against time in CSU's (horizontal axis). The scatter of points is then used to define a depth versus time relationship in LOCs, drawn with respect to an evaluation of individual data points (figure 2.2). Fossils that do not fall on the LOC may not achieve their full range in sediments from the comparison well and plot below the LOC. Additionally, fossils plotting above or to the left of the LOC could be reworked occurrences or they may indicate that the chronological position of the particular datum needs to be updated in the composite standard (figure 2.2). This procedure requires a knowledge and interpretation of the expected and observed biostratigraphic succession. The LOC approximates relative sediment accumulation rates (not accounting for differential compaction) as resolvable by the fossils (Shaw, 1964). Interpretation of the biostratigraphy in this example identifies at least two horizontal terraces in the LOC, representing missing or condensed section, separating sloping line segments characteristic of higher depositional rates (Sediment Pulse). Also plotted are fossil tops occurring out of normal succession due to local environmental conditions. These occurrences can distort chronostratigraphic frameworks that are based exclusively on key markers (Stein *et al.*, in press). For example, in figure 2.2, fossil G plots above and to the left of the LOC, indicating an extended range or reworked occurrence. This observation has important implications for correlation of stratigraphic breaks. The FDO of fossil G
is normally found above the FDO of F and below the FDO of H, according to the
chronostratigraphic range chart. In the example well, the FDO's of fossils F and
H define a stratigraphic break that would normally contain the top of fossil G. If
fossil G is regionally used as the key marker for this break, a significant amount
of section falls within an incorrect chronostratigraphic unit.

The geologic interpretation of a LOC terrace has great importance in
determining its position within a sequence stratigraphic interpretation.
Paleobathymetry estimates are a key piece of information when considering the
cause of an terrace. Figure 2.2 has a paleobathymetry estimate of bathyal
depths for the entire section. Given that the section is mostly sand, with some silt
and shale interbeds, an interpretation of stacked sandy turbidites in a
submarine fan is reasonable. In this setting, LOC terraces are usually related to
sediment starvation. This is not always the case in shallow section that record
sea level change more directly. Figure 2.3 illustrates the theoretical relationship
of graphic correlation terraces within a sequence stratigraphic model of two
depositional sequences. This model has been modified to reflect the separation
of the highstand and transgressive shelf from lowstand basinal deposits, as is
the case in the North Sea Paleogene (Armentrout et al., 1993; Chapters 3 & 4).
In this idealized model, biostratigraphic resolution is assumed to permit the
recognition of each systems tract. A well through submarine fan deposits (Well
C) will have the simplest pattern of deposition with short periods of rapid
sedimentation being separated by longer intervals of sediment starvation (see
also figure 2.2). A sequence boundary occurs at the base of each depositional
package, as major fan deposition results from falls in sea level (Kolla and
terraces between depositional pulses contain the chronostratigraphic
Figure 2.3. Model for the integration of graphic correlation offsets with key bounding surfaces in sequence stratigraphy. In the graphic correlation interpretation, sequence boundaries are drawn as stippled lines in time where they begin to form (i.e., with the first relative fall of sea level). The dashed LOC represents a possible brief offset at the maximum flooding surface.
equivalent distal drape deposits of the lowstand prograding, transgressive and highstand systems tracts (time B-D). If deposition can be demonstrated to be continuous, although at a greatly reduced rate (<1 cm/ky), across this interval, then the package is correctly termed a condensed section. However, if sampling is insufficient to document continuous sedimentation, or hiatuses can be demonstrated, additional complications arise that will be discussed below.

A well near the lowstand shelf edge (Well B) should show a similar pattern of accumulation and nondeposition as the fan setting, however, some differences are noted in the position and interpretation of LOC terraces. The first difference is the time of deposition below the first terrace. In Well C, accumulation took place between time A and B (figure 2.3). Well B accumulation extends to time C as this well encounters lowstand shelf deposits that are distally starved in Well C. The sequence boundary (time D) occurs within the LOC terrace, demonstrating a division between lack of accumulation due periods of sediment starvation and bypass. The time of bypass (time D to E) is represented by deposition above the sequence boundary in Well C. For time E to F, Well B records only the deposition of lowstand shelf sediments.

Updip wells have the most complex pattern of sediment accumulation as coastal processes of wavebase and subaerial erosion compete with variable sediment supply and sea level change. This simplified 2-D model assumes a constant deposition in the plane of section where sediment supply attempts to fill shelfal accommodation space created by relative sea level change. The solid LOC for Well A shows a single terrace, commencing with the sequence boundary (time D) and ending with renewed deposition at the next transgression (time F). This terrace reflects nondeposition due to subaerial exposure. The maximum flooding surfaces between times C-D and F-G might
be associated with a small terrace (dashed line) due to a brief period of sediment starvation or wavebase erosion. Should any subaerial erosion occur, the terrace from D to F will be extended back in time to capture the time of deposition removed by this erosion. Theoretically, there should exist an instant of time that is contained within a LOC terrace for wells in each setting. This instant corresponds to eroded section in Well A, the point where starvation becomes bypass in Well B and the time just before sedimentation resumes in Well C. If this overlap of terraces in time can be demonstrated, then a chronostratigraphic unit (depositional sequence) is documented. Of course the real world is seldom so well behaved.

Complications caused by nested stratigraphic cycles

Recent papers have recognized an increasingly higher frequency sea level signal within the sequence stratigraphic model (e.g. Mitchum and Van Wagoner, 1991; Posamentier et al., 1992). This adds a potential complication to correlations throughout a basin. Basinwide correlations must consider the effect of nested high and low frequency sea level changes. During low frequency sea level falls, high frequency falls will have greater relative magnitude (Mitchum and Van Wagoner, 1991) and regressive pulses will occur into deeper parts of the basin. Updip sections may only encounter a single exposure surface spanning the time of a multi-sequence regression in the basin. Conversely, low frequency rises in sea level may subdue expression of high frequency falls in the deep basin while stacking thick sedimentary packages at the basin rim. These packages may record a relative sea level signal that is unresolvable in the deep basin (figure 2.4).

The graphic correlation expression of these backstepped packages depends again on biostratigraphic resolution. With a perfect resolution similar to
Figure 2.4. Possible complications in the resolution and correlation of events when deposits from a high frequency sea level signal are preserved on a low frequency sea level rise. High frequency events are correlated within low frequency cycles except where sediment supply or data resolution allows for their separation.
figure 2.3, the ideal LOC of a well penetrating this section (Well A) can potentially resolve high frequency events. The relative sea level curve (figure 2.4) shows a low frequency rise with superimposed high frequency events. These high frequency cycles are of smaller magnitude than their carrier and the sediment response is of an equally smaller magnitude when compared to the regressive wedge penetrated by Well B (figures 2.3 & 2.4). The smaller events cause a period of subaerial exposure similar to larger falls, however, deposition during relative lowstand of sea level is restricted to the inherited shelf. Little, if any, sediment reaches the shelf-slope break. This is caused by an excess of shelfal accommodation space that the sediment flux from sea level falls at \( c' \) and \( c'' \) cannot fill.

Although smaller in magnitude, deposition during this sea level cycle has all the characteristics necessary for a depositional sequence and should be identified as such (Mitchum and Van Wagoner, 1991). Given perfect preservation and biostratigraphic resolution, the LOC for a well through this section (Well A) will record small terraces, caused by the brief period of subaerial exposure (figure 2.4-time following \( c' \) and \( c'' \)). A more distal well (Well B) may only recognize the low frequency signal, illustrating the need for careful correlation of events to avoid mistying high frequency surfaces to low frequency deposits.

The possibility of a mistie has great significance in a sequence stratigraphic analysis. One of the first principles of sequence stratigraphy is that relative changes of sea level are a function of changing tectonic subsidence and eustasy (Vail, 1987). Eustasy is defined as *global* changes of sea level (Seuss, 1906; Fairbridge, 1961), therefore, eustatic events should have some expression in deposits of a given age worldwide. This concept was tested at
Exxon by P.R Vail and co-workers, then published in charts relating coastal onlap of sediments to eustasy (Vail et al., 1977a; Haq et al., 1988). A common criticism of this work was the lack of precise documentation used to tie sequence boundaries around the world. Aubry (1991) examined this problem for an interval at the top of the Lower Eocene. With detailed stratigraphic resolution from many sections around the world, she documented the complexity of sedimentation for this interval to be greater than that predicted by a simple, two-event model proposed by Haq et al. (1988), although the global signal of two events ("49.5" and "48.5"-Haq et al., 1988) could be recognized.

The challenge in this type of documentation rests in precise age-equivalent correlation of events. Figure 2.5 (modified from Aubry, 1991) demonstrates the need for caution and precision when correlating stratigraphic gaps. Section A (in depth) shows an unconformity, separating younger from older sediments. This unconformity can be thought of as two time surfaces, the lower representing the time of subaerial exposure down to the oldest eroded bed and the upper surface corresponds to the time of resumed deposition. These surfaces bracket an interval of geologic time not represented by rock in Section A. Sections C and D contain unconformities of similar age to the unconformity of Section A, however, detailed stratigraphic investigation reveals that the unconformity in Section C erodes rocks that are younger than rock directly overlying the unconformity in Section D. This suggests that the unconformities of C and D are of different ages, yet both overlap in time with the unconformity in Section A. A correlative stratigraphic gap is not shared by all three sections, therefore, we are left with two choices: (1) the unconformities are caused by local conditions (tectonics, current scour, dissolution, etc.) and no eustatic signal is observed or, (2) the eustatic signal is expressed in some way other
Figure 2.5. Diagram of unconformities in three sections (modified from Aubry, 1991). Section A is shown in depth and geologic time. The hiatus in section A could have been formed by either Event 1, Event 2, or a combination of both. The unconformities in sections C and D could not have been caused by one (eustatic) event, since they do not overlap in time (see text for discussion).
than an unconformity in one of the sections (e.g. sharp change in sedimentation rate). For each case, documentation of a eustatic signal is dependent upon demonstration of chronostratigraphic equivalence for a chosen stratigraphic marker.

Graphic correlation addresses this problem by constructing a consistent biostratigraphy and demonstrating LOC terraces that overlap in time for multiple sections. In many cases, the graphic correlation approach is preferred over the condensed section method of Loutit et al. (1988) for reasons discussed in Chapter 4. Figure 2.6 presents an idealized situation that highlights the need for caution when using “condensed section” terminology. This diagram expands the section around the LOC terrace at 5630 ft in figure 2.3 and displays how a major LOC terrace may contain multiple sequences. This well could represent a downdip well, basinal to figure 2.4, where fossils F and H correspond to times c” and D, respectively. The term, "hiatal interval" (Chapter 4), provides a conservative means of relating LOC terraces to real geology. In a study that relies on ditch cuttings for data collection, hiatal interval correlation seems the most conservative and flexible way to build a meaningful chronostratigraphic framework.

**Graphic Correlation and Sequence Stratigraphy Integration**

**Examples**

Now that the theoretical applications and complications have been presented, the reader may feel either apprehension at all the caveats of this method or excited at the possibilities it offers for correlation. In real data, graphic correlation will almost certainly not resolve all key stratigraphic surfaces in the rock. It will also not tie exactly with key surfaces for two reasons: (1) sampling of the biostratigraphy will likely be at a coarser interval than necessary to resolve
Fig. 2.6. - Diagramatic illustration of possible stratigraphic complexities (Actual line) around a hiatal interval with an interpretation of biostratigraphy from cuttings using graphic correlation and a condensed section approach. Data points are plotted at the base of each sample interval as they appear in standard well reports, the "Actual" line is based on the exact position of each marker in a cored section (see text for discussion).
some of the more condensed intervals, and (2) biostratigraphy is limited by
available markers. If, for example, calcareous nanofossils are used for
correlation, it is likely that more than one important surface will fall within each
zone. This leads to an aliasing problem where the resolution of a tool (nanno
zones) is coarser than the resolution of what is being measured (stratigraphic
position of key surfaces). Graphic correlation will, however, provide a
consistent, integrated biostratigraphy, and it will allow a demonstration of
chronological correlation with the maximum available biostratigraphic
resolution.

The following examples of graphic correlation integration with sequence
stratigraphy come from a regional study on the Paleogene of the Central North
Sea subsurface, correlated to Paleogene outcrops in NW Europe using graphic
correlation (Stein et al., in press; Chapter 4). Sequence names come from
lithologic units in the area and are not important for this discussion. A 30 m
‘error bar’ between the reported fossil depth occurrence and the well log pick
was used by Armentrout et al., (1993), to account for operator consistency and
seismic resolution. Using this margin of error allows great freedom in making a
sequence pick fit well and seismic data. Generally, agreement was reached
between at least two of the three disciplines used in this study (log
interpretation, paleontology, and seismic interpretation). The error bar
mentioned by Armentrout et al., (1993) is one way to reconcile a mistie of
biostratigraphy with well log and seismic interpretation. When sequences are
below seismic resolution or occur within a seismically chaotic zone, well log
interpretation and fossils are the only tools that allow correlation with any
confidence.
Sequences are picked on individual well logs based on an interpretation of the relative sea level signal for each particular location, correlated with biostratigraphy. For example, in deep water settings, the base of the Upper Sele sequence occurs at a high gamma marker on electric logs near the reported acme occurrence of the dinocyst *Cerodinium wardenense* (Williams & Downie, 1966) from cuttings. The sequence boundary is interpreted to be combined with the underlying maximum flooding surface (Vail, 1987; O’Connor and Walker, 1993). The sequence boundary marks renewed basinal deposition due to a fall in relative sea level and shelfal bypass, depositing sediment containing abundant *C. wardenense*, capped by hemipelagic drape containing abundant *Deflandrea oebisfeldensis* (Alberti, 1959). In shelfal settings, the sequence boundary can occur at the base of a thick coal, an incised valley deposit, or at the base of a transgressive sandstone. The coal represents the remains of a marsh and a base level zero datum (Milton *et al.*, 1990). Thick, rooted coals are indicators of transgression (Cross, 1988), therefore, their bases are likely exposure surfaces. Not all coals overlie sequence boundaries, however, as the Balder sequence (Beauly Formation) contains many coals that are discontinuous and simply reflect delta lobe abandonment within an overall transgressive package.

**Basinal setting**

The composite standard for the Central North Sea has been largely built and utilized in the deep marine environment where correlation of turbidite packages relies on good biostratigraphy. A sequence stratigraphic interpretation involves a series of steps that begins with interpretation of the biostratigraphic data, followed by picking sequences on the well logs that are tied to seismic with synthetic seismograms, and finally correlation with seismic data between well
control points. Figure 2.7 is a typical basinal well for the North Sea Paleogene with gamma ray curve, lithology and the biostratigraphic top or acme datums from a well report. Plotted to the right of the well are biostratigraphic datums at their reported depth and relative age within the composite standard for the Central North Sea (in non-linear composite standard units). A LOC is interpreted with the scatter of points. Since the composite standard for the North Sea was built using North Sea wells, individual wells are plotted against the standard in later iterations minus the well itself, to avoid a circular interpretation.

Where graphic correlation identifies a hiatal interval, it is possible to place a sequence boundary on well logs at, or near the interval, using the 30 m 'error bar'. Often, high gamma shales are used to pick genetic sequences (Galloway, 1989; Stewart, 1987). These high gamma intervals, which are interpreted to represent very slow sedimentation, divide the section stratigraphically into sediment pulses. In a basinal well, sequence boundaries are picked at the base of each sediment pulse (see figure 2.3). In the deep marine environment, this approach is possible because highstand and transgressive deposits are not well-represented and result in merged sequence boundaries and maximum flooding surfaces (Vail, 1987). However, in a sand-rich turbidite environment such as the Paleogene Central North Sea, submarine scouring may produce a sequence boundary in wells that is locally a sand-on-sand contact. Choosing a log marker to designate as the sequence boundary must rely on the biostratigraphy. Unfortunately, not all log and seismic sequences in this study were resolvable with the graphic correlation tool. However, LOC terraces served to bracket sequences that are picked on the basis of seismic and well evidence.

A basinal well 15 km to the east is interpreted in the same manner as figure 2.7 to correlate sequences and demonstrate how sediment distribution within
Fig. 2.7 - Graphic correlation and sequence stratigraphic interpretation of UK well 16/28-1. Data points are first downhole and acme occurrences of various taxa, distinguished by symbol. Paleobathymetry is given as bathyal and open marine for the entire section (paleobathymetry estimates courtesy S.P.T. - Robertson Research). Lithology symbols: \(\square\) = chalk, \(\square\) = isolated limestones, \(\square\) = shale, \(\square\) = silt, \(\square\) = sand, \(\square\) = tuff.
sequences changes (figure 2.8). The Lower Balmoral sequence (2475 m and 2775 m) in figure 2.7 is a thick stack of sandy turbidites that becomes a thinner, silty interval in figure 2.8. The Maureen sequence sands of figure 2.7 between 8870 ft and 9130 ft are calcareous claystone in figure 2.7 (2850 m - 2825 m). Additionally, the LOC terrace above the U. Forties sequence in figure 2.7 merges with an terrace above the Upper Balmoral in figure 2.8, demonstrated a longer stratigraphic break in the LOC of figure 2.8 at this position. Individual biomarkers defining each sequence may vary slightly. Fossils that define a sediment pulse in one well may be found in hialtal intervals above or below the sequence in another well, but the markers should not define a sediment pulse for a different sequence (e.g. the acme of *Palaecystodinium bulliforme* (Ioannides, 1986) is within the sediment pulse of the Andrew sequence in figure 2.8, but occurs in the hialtal interval below the sequence in figure 2.7). Individual markers are found in different sequences if they occur out of normal succession (i.e. the LOC does not pass through them—see figure 2.2 for example). This is an important advantage graphic correlation has over stratigraphic frameworks based solely on individual markers.

*Tying to seismic data*

Tying the well data to a seismic line with synthetic seismograms is a critical step in supporting correlations, since seismic reflectors follow geologic time lines (Vail et al., 1977b). Plotting the LOC of a well next to the time-converted gamma ray curve directly ties relative geologic time, as resolved by the biostratigraphy, to a seismic line (figure 2.9). This plot provides information concerning the variable duration of geologic time represented within the seismic section. Hialtal intervals correlate, within resolution limits, to regionally mappable seismic reflectors. Figure 2.9 illustrates that some intervals are below
Fig. 2.B. - Graphic correlation and sequence stratigraphic interpretation of UK well 16/29-4. Data points are first downhole and acme occurrences of various taxa, distinguished by symbol. Paleobathymetry is given as bathyal and open marine for the entire section (paleobathymetry estimates courtesy S.P.T. - Robertson Research). Lithology symbols: ☐ = chalk, ☐☐☐ = isolated limestones, ☐☐☐☐ = shale, ☐☐☐☐ = silt, ☐☐☐☐ = sand, ☐☐☐☐ = tuff.
**Fig. 2.9.** - Synthetic seismogram tie of the UK 16/28-1 well (Figure 2.7) to a regional seismic line. Graphic correlation and gamma log are time/depth converted to tie with the seismic data. This display illustrates how relative geologic time can be directly tied to seismic time. See Figure 2.7 for correlation of sequences as some sequences are below seismic resolution. (see text for further discussion).
the resolution of this seismic data and are represented by a single wavelet peak or trough. These intervals are correlated on wells until a thicker section permits seismic resolution.

Sequences that are distinguishable on seismic data show remarkable lateral facies and thickness variation. Figure 2.10 illustrates how the seismic, well, and biostratigraphic correlations are integrated to resolve complex lobe deposition in two dimensions. The seismic line shows complex stratal termination patterns associated with deposits in a submarine fan setting (Posamentier et al., 1991). Correlations of well and biostratigraphic data help construct a sequence stratigraphic model highlighting the potential for multiple stratigraphic traps. Sandy turbidite depositional sequences, sourced from the west and depositionally pinching out to the east have considerable proven reserves for various Paleocene sequences (e.g. Sarg and Skjold, 1982; O'Connor and Walker, 1993).

Plotting both graphs together with the same horizontal (time) scale highlights time-correlative stratigraphic breaks (figure 2.11). For example, datasets from wells 16/28-1 and 16/29-4 both show LOC terraces from 860 to 910 CSU. Both wells experience condensed sedimentation or erosion during that period, which demonstrates a correlative break in rock accumulation. Major breaks may contain more than one terrace as shown at location A (figure 2.11). Even time intervals of small correlative breaks (i.e., location B, figure 2.11) identify depositional sequences, regardless of lateral facies changes. Figure 2.11 also brings out the variable nature of rock accumulation between the correlative terraces in time and space. In a submarine fan setting, sedimentation is complex and varies greatly in depositional rate along strike and dip (Walker, 1978). Where both wells share a time interval of no rock accumulation, the overlapping
Fig. 2.10. - Seismic and well log cross section between 16/28-1 and 16/29-4, illustrating the rapid lateral facies shifts that are seen in this area. Numbered sequence boundaries that start with \( S_1 \) (K/T boundary) on the interpreted seismic are displayed in the geologic cross section. Between sequences \( S_3, S_4 \), & \( S_5 \) are additional sequences, identified and correlated on logs, highlighting the limiting seismic resolution when correlating surfaces. Seismic data courtesy of GECO-Prakla & Nopec.
Figure 2.11. Composite graph of line of correlations for two Central North Sea wells with overlapping time gaps indicated. Location (A) shows the collapse of two offsets into one and location (B) shows correlation of even short duration events (see text for further discussion).
data terraces are interpreted to represent correlative events bracketing sediment pulses. Regional correlation is necessary to verify that the stratigraphic breaks are basinwide events. Deposits between terraces do not necessarily have to overlap in time due to the episodic nature of submarine fan sedimentation. The different lengths of terraces between wells is explained by considering fan lobe avulsion and its effects on a LOC.

**Shelfal setting**

A different depositional setting is considered in the next example as shelfal environments are encountered. Figure 2.12 shows the gamma curve, lithology, graphic correlation and sequence stratigraphic interpretation of a well through the Upper Paleocene shelf. Critical to the interpretation of this section is the paleobathymetry column estimating the depositional environments of these sediments using benthic forams and other indicators. Sequence and systems tract picks come from well log interpretation of depositional environment (Vail, 1987; Vail and Wornardt, 1990) and basinward shifts in facies, however, log patterns alone are not diagnostic. For example, the sand at a depth of 3500 ft has a log pattern similar to other sands below 4600 ft. Paleobathymetry estimates places the upper sand in the transitional marine to inner shelf environment while the lower sands were deposited in an upper bathyal water depth. The lower sands represent fan deposition (Lower Lowstand-figure 2.1) during falling sea level and the upper sand is interpreted as incised valley fill during rising sea level. The paleobathymetry alone can track low frequency sea level cycles with peak floodings around 4500 ft and 2700 ft.

The LOC for this well has few terraces, but they provide some interesting information. The first observation that can be made is that more sequences are identified on the well log than are reflected in the LOC. Sequences are
Figure 2.12. Sequence stratigraphic interpretation of a well with shallow water section. Systems tract interpretations are based on log character and paleobathymetry: LLST=lower lowstand (bypass sediments), ULST=upper lowstand (lowstand prograding and slumps), TST=transgressive systems tract, IVF=incised valley fill, HST=highstand systems tract. Paleobathymetry courtesy of S.P.T. (Robertson Research). Lithology: ⬤ = limestone, ⬤ = marl, ⬦ = sand, ⬤ = silt, □ = shale.
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**Graphic Correlation**

Increasing CSU/Decreasing age →

- 30 m "error bar"

--- possible LOC using "error bar"

**Key to Fossil Groups**

- # Pollen
- * Dinocysta & Acritharcha
- ~ Siliceous microfossils
- † Planktic foraminifera
- X Benthic foraminifera
correlated within LOC terrace-bounded units. This problem was discussed above and requires regional work be done to document sequences picked on physical surface criteria (wells and seismic-see below). Another point is made by the terrace at approximately 3700 ft depth, which corresponds to a high gamma marker interpreted to be a maximum flooding surface. In this case, the terrace may be caused by starvation or wavebase erosion (e.g. Well A, figure 2.3). Another possibility is that environmental conditions caused an terrace to form here because water depths for overlying deposits are very shallow, with samples containing only pollen and spores. With this real data set, resolution of the type described in theoretical models above is not achieved. The terrace in the shelf well overlaps with similar terraces found in distal wells. Clearly the mechanism for the formation of an terrace in the shelf well will differ from basinal ones, however, if terraces in each location contain similar fossils, they will necessarily occupy the same time. The ideal should be considered, but reality dictates the actual data. It is up to the interpreter to realize and communicate these limitations. This does not invalidate the chronostratigraphic correlation, it simply requires an awareness of the resolution limits.

The “terrace” across the Lower Eocene section in this well highlights another limitation, which is data sampling. The LOC has a gradual slope as dictated by the data, however, paleobathymetry estimates note a rapid deepening above 2900 ft. The sand between 2900 ft-2700 ft is interpreted as a lower lowstand deposit, due to the upper bathyal water depth estimate. A possible explanation for the scatter of data points is that rapid deepening occurred above the section deposited at 2900 ft. A great deal of time may be represented in deposits below the Lower Eocene sand, but the sand was deposited by gravity flow processes that reworked fossils from the underlying “condensed section".
This unit highlights why "hiatal interval" terminology is preferred over "condensed section". The Lower Eocene sand was probably deposited rapidly, despite the gradual slope of the LOC. Most of the time for this interval is likely represented in section above and below the sand, however, sampling resolution is unable to verify this. The Lower Eocene spans 5 Ma according to Haq et al. (1988). If the sand is assumed to be deposited by turbidite events, then most of that 5 Ma must be accounted for in the very thin high gamma shales above and below this unit. Sedimentation rates necessary to accommodate this amount of time in such thin units are well under 1 cm/ky, unrealistically low for an intracratonic basin such as the North Sea without accounting for periods of erosion (Sadler, 1981). Since hiatuses are difficult to recognize from electric logs, the conservative interpretation would be to recognize that hiatuses occur in this section without directly determining their exact location. If "error bars" for each datum through the Lower Eocene section are used, a possible LOC can be interpreted, however, this approach creates an interpretation not easily supported by the raw data and is not recommended. The conservative LOC is preferred to highlight the biostratigraphic correlation and require that further interpretation of the section involve well log analysis. Error bars are best used to place individual cutting samples with their appropriate log marker, rather than force a biostratigraphic interpretation of a terrace when no individual sample supports this interpretation.

Enhanced correlation on the shelf using seismic

Shelfal sections often have problematic LOCs when using a composite standard built mainly from basinal wells. The advantage shelfal wells have over their distal counterparts is that deposits resulting from sea level changes are more easily distinguished from autocyclic deposits. In the basin, sea level
changes are determined indirectly by recognizing sediment pulses as resulting from sea level fall and linking drape deposits to periods of high sea level. Without good chronostratigraphic control, any rapid increase in sedimentation rate might be mistaken for a separate depositional sequence when, in fact, it could result from fan lobe avulsion. In shallow sections, basinward shifts of facies are the clearest indicator of sea level change. Shallow sections, if thick enough, also display seismic stratigraphic patterns that relate to changes in sea level (figure 2.3). The correlation of wells to seismic in a shelfal setting can provide additional support for sequences that may be biostratigraphically unresolvable.

Sequences picked on less than convincing evidence in one well may be verified by correlation to neighboring wells and seismic data (figure 2.13). Sequences constrained between LOC terraces may or may not have exactly the same time of intercept with the LOC between terraces. The Middle and Upper Sele sequences show this relationship when correlating between wells 15/6-1 and 15/13-2. These two wells have been interpreted for depositional sequences and tied to seismic with synthetics. The Sele sequences are picked at physical surfaces in the wells and on seismic (figure 2.13). In the 15/6-1 well, both sequence boundaries are picked at the base of transgressive sands, indicated by upward increasing gamma values. The Upper Sele sequence has highstand progradation (see figure 2.12) that rapidly thin towards the shelf break (figure 2.13). In well 15/13-2, a slope sand rests on the M. Sele sequence boundary and the sand is capped with mudstone equivalents of updip transgressive and highstand deposits. A carbonate layer marks the Upper Sele sequence in this well. This bed may represent a hardground omission surface that is unresolvable with biostratigraphy with the overlying silty section interpreted as lowstand deposits. These sequences fall between two overlapping terraces, but
Figure 2.13. Correlation of depositional sequences in a shelfal setting by well log and seismic interpretation and graphic correlation. Lithostratigraphic units are from Robertson Research. Lithology key is: ▲ = sand, ▶ = silt, ▼ = shale, ▽ = carbonate. Seismic data is courtesy S.P.T. (Horizon Geophysical).
do not intersect the LOC at precisely the same time. They are
chronostratigraphic units nonetheless, as demonstrated on seismic.

The LOC for 15/13-2 distinguishes terraces in the Lower Eocene section
(Frigg Undif.) that are not apparent in 15/6-1. The Frigg Undif. section has been
subdivided into at least three separate sequences (discussed below), and the
LOC for 15/13-2 hints that this is possible. Correlation with LOC terraces
provides some information on the chronostratigraphic equivalence of the
"Dornoch" deltaic lithostratigraphic unit, which is apparent on seismic data. This
correlation suggests that the lower prograding unit of the Dornoch in 15/6-1
(~4000 ft-3600 ft) falls within a different chronostratigraphic unit the lower
prograding of 15/13-2 (~1560 m-1410 m). Tying well picks to seismic confirms
this correlation as a deeply incisive sequence boundary separates the overall
prograding package into two distinct units. As a side note, this section also
supports the interpretation of these prograding units as lowstand since the base
of the incisive canyon occurs at the same depth as the first toplap (Mitchum et
al., 1977) in the eastern prograding package. Toplaps in deltaic units are
considered to represent baselevel in true dip sections (Mitchum et al., 1977,
Milton and Jones, in press), and by calculating from seismic conversion the
depth at the top of a prograding package to the depth of the first toplap in a
subsequent progradation, a minimum estimate of sea level fall is obtained. The
physical relationship of deposits in this example (figure 2.13) suggests that sea
level fell at least 150 m.

*Shelf to basin correlations*

Correlation of two or more wells that were deposited in the same
environment (e.g. shelfal-figure 2.13 or basinal-figure 2.10) is a fairly
straightforward exercise with good biostratigraphic and seismic control. A more
difficult task is the correlation of wells in the basin to those on the shelf. The theoretical relationship of LOC terraces to depositional systems tracts (figure 2.3) must be considered while dealing with actual situations and raw data. It is unlikely that all aspects of the theoretical model will be observed, however, certain aspect of the model can be applied to explain observed departures from precise correlation of units. Correlation of two wells having very different depositional environments is attempted in figure 2.14. Well 8/27a-1 is situated on the East Shetland Platform in the North Sea and penetrates a thick shallow water section as evidenced by well-developed coals and verified with paleobathymetry estimates that are inner shelf to transitional for much of the section. Conversely, well N25/1-3 on the Norwegian side of the South Viking Graben never gets shallower than upper bathyal. This well penetrates thick sequences of submarine fan sands that should be genetically linked to shelfal deposits according to the sequence stratigraphic model.

Data are sparse through the shallow section of 8/27a-1, but a LOC can be drawn to honor as many points as possible, resolving numerous LOC terraces. Using these interpretations, several observations can be made. In the lower sections, both wells penetrate deep water deposits and the LOC terraces match closely. As section in 8/27a-1 shallows, both wells record a “top Forties” terrace that was recognized in figure 2.7, collapsed in figure 2.8, and not resolved in figure 2.13. The position of this terrace is interesting in that a very narrow overlap between the two wells can be seen around 710 CSU. Using the error bar to relate biostratigraphic data to well depth, this terrace can be placed near the base of a thick coal in 8/27a-1. This terrace in N25/1-3 starts and ends earlier than in 8/27a-1 as would be suggested from the model (wells A and C-figure 2.3). In well N25/1-3, the upper package of sandy fans is divided into two
Fig. 2.14. - Composite plot of graphic correlation comparing the shelfal UK 8/27a-1 and basinal (Frigg Field) N 25/1-3 wells with overlapping LOC terraces from these wells and Figure 11 shown at the top. Lithology key: [ ] =Cretaceous limestone, [ ] =isolated limestone, [ ] =sand, [ ] =silt, [ ] =shale, [ ] =coal. 1Paleobathymetry zones: 1. Transitional/Marginal marine, 2. Inner shelf, 3. Outer shelf, 4. Upper bathyal, 5. Middle to Lower bathyal (courtesy of S.P.T. - Robertson Research).
sequences, Lower and Middle Frigg. Most of the time represented by these deposits falls into a LOC terrace in 8/27a-1, suggesting a long period of bypass at the 8/27a-1 site while significant accumulation occurred at the N25/1-3 site. At the top of the Frigg package in N25/1-3 (~1950 m), a long terrace appears in the LOC. During this time interval, a thick progradational package is deposited on the shelf (~2650 ft-2270 ft in 8/27a-1), and it is even possible to recognize more than one sequence. This example of sediment partitioning is similar to figure 2.4.

The importance of these observations is apparent when trying to construct a basin analysis using sequence stratigraphy. Sequences will not be obvious in all parts of the basin, but with a composite biostratigraphy, depocenters from all parts of the basin may be fitted into a complete chronostratigraphic framework. Resolution of events depends on sedimentation rate and the resolution of the age dating tool. Even time intervals of overlapping terraces in one part of the basin may be expanded into thick sections for another area. Figure 2.15 demonstrates how the time of overlapping terraces below the Frigg package ("Balder" terrace) expands into 100 m of section in a cored borehole from onshore Germany. Sequences are identified by increasing and decreasing value trends on the gamma log, related to sea level change as a function of silt content. An ideal composite will incorporate all depocenters in a basin then determine in later graphing rounds what intervals are missing for any particular section.

**Discussion, Pitfalls, and Implications for Stratigraphy**

Clearly, the integration of sequence stratigraphic and graphic correlation methodologies has potential to be a powerful tool in the basin analysis. Graphic correlation also has the potential to bring a systematic documentation to
Fig. 2.15. - Graphic correlation of dinoflagellates in the North German Würsteralde borehole from Heilmann-Clausen and Costa (1999). In this section, the overlapping "Balder" LOC offset from the North Sea corresponds to an interval of deposition. Interpretation of gamma ray log identifies depositional sequences that are observed elsewhere in Northwest Europe.
questions about the role of eustasy in sequence stratigraphy. The key to this procedure is for the user to be aware of all the possible complications in its application. There is an idealized relationship between LOC terraces and sequence stratigraphic bounding surfaces, but the link depends on correct application of both procedures and is then limited by the data resolution. The examples presented here come from an area with exceptionally rich biostratigraphic data due to continuous study for many years. In frontier areas, the technique is no less valid. Any stratigraphic study is limited by resolution of the available data, be they discontinuous outcrops, sparse well data or coarse biostratigraphic resolution. Workers at outcrop scale have different resolutions from those using multichannel seismic data. The fractal nature of geology ensures that no stratigraphic study will be able to record and correlate all events, but by integrating the available stratigraphic techniques, it is hoped that some key bounding events can be confidently recognized and correlated. By compositing whatever data are available, a chronostratigraphic framework is constructed. As more data become available, the composite standard becomes more complete. Observations made on the rocks being studied do not change. The interpretation of those observations and their position within a chronostratigraphic framework may change as new information becomes available.

Sequence stratigraphic theory has developed as the resolution of seismic data improved. The coastal onlap curve of Vail et al. (1977a) was not invalidated by revisions in Haq et al. (1988), rather the resolution of events improved and more cycles were added to the original curve. As sequences have been observed at increasingly brief time intervals, a need to distinguish between magnitudes of cycles develops. A sequence stratigraphic study needs
to be regional if it hopes to recognize the different magnitudes of cycles.
Recognition of a global signal (eustasy) will subsequently require study on a
global basis. Graphic correlation can help in this endeavor. A composite in its
early stages should recognize major stratigraphic breaks (continental floodings,
basin forming events, or plate tectonic reorganizations). Within these major
stratigraphic units, smaller magnitude events can be correlated as stratigraphic
detail is infilled. The confidence of correlation for smaller duration events is
directly related to the resolution of the correlation tool being used (marker beds,
biostratigraphy, magnetostratigraphy, isotopes, etc.). All types of chronological
information may be carried in a composite at any time scale.

Chapter Conclusions

The actual construction of a composite standard is conceptually fairly
straightforward. Find the most complete stratigraphically overlapping sections in
a study area to have an idealized complete section for the entire time interval
being studied. By testing subsequent sections against the composite,
stratigraphic gaps may be observed in the test section that are complete in the
composite. Demonstration that stratigraphic gaps overlap in time between two
or more sections establishes a framework of chronostratigraphic units.
Sequence stratigraphy is based on the concept that sequence boundaries are
time markers, separating younger deposits from older ones. Graphic correlation
can document this relationship within the limits of whatever chronological tool is
being used for control. When applied with caution, the integration of sequence
stratigraphy and graphic correlation documents a chronostratigraphic
framework that remains flexible for future work.
Chapter 3

Nested Stratigraphic Cycles and Depositional Systems of the Central North Sea Paleogene

Chapter Summary

A sequence stratigraphic analysis of subsurface data from the Central North Sea Paleogene has documented a stratigraphic framework of 18-21 "third order" depositional sequences nested within 5 "second order" major regression/transgression cycles. The order of a cycle is based on observations concerning its constituents and its impact on the depositional systems of the basin, not strictly on its duration. Integration of the composite standard biostratigraphic method enabled the construction of a consistent chronostratigraphy based on the correlation of hiatal intervals identified with graphic correlation data terraces. An ideal relationship of graphic correlation terraces within a sequence stratigraphic model is diagrammed, providing the theoretical basis for the correlations presented. A depositional model is also proposed as a variant of the classic Vail model, considering the effect of depositional profile and sediment supply in the preservation and distribution of systems tracts. Recent revisions in Central North Sea lithostratigraphy and sequence stratigraphy provide an opportunity for comparison between different methods and data resolutions.

Introduction

The idea that natural cycles can occur at many different time scales and be "self similar" has gained popularity with the advance of fractal theory (Mandelbrot, 1983). Depositional sequence stratigraphy (Vail, 1987; Van Wagoner et al., 1988; Vail et al., 1991) developed from seismic stratigraphy
(Mitchum et al., 1977), and has seen a similar trend towards recognition of higher frequency signals. Papers by Mitchum and Van Wagoner (1991) and Posamentier et al. (1992a) highlight sequences at much higher frequency than suggested by the eustatic curve of Haq et al. (1988). In basin analysis, recognition of the different “orders” of stratigraphic cycles and their interaction complicates the identification of a unique basinwide correlation. Reservoir studies are conducted with dense data control and may be unconcerned with the regional consequences of recognizing the “global signal” for correlation. Basin analysis work must place observations at any one location into a stratigraphic framework for all other locations in the basin. Constructing a stratigraphic framework of nested stratigraphic cycles is one way to identify a more complete basinwide sea level history.

The Central North Sea Paleogene section is a good place to test this approach since many years of hydrocarbon exploration has built an extensive seismic, well log, and biostratigraphy database. Exploration by numerous companies has resulted in a convoluted stratigraphy with many different lithostratigraphic names for time equivalent deposits. By constructing a stratigraphic framework for the Central North Sea Paleogene, based on sequence stratigraphic interpretation of seismic, wells, and graphic correlation of all biostratigraphic datums (not biostratigraphic zones), we will demonstrate the nesting of 18 - 21 “third order” depositional sequences within 5 “second order” major regression/transgression packages.

**Previous Studies**

The stratigraphy of the lower Paleogene section of the Central North Sea has evolved with the development of higher quality seismic data and numerous well penetrations since the first basinal studies of Parker (1975) and
lithostratigraphic nomenclature of Deegan and Scull (1977). Major field
discoveries in the late 60's and early 70's focused mainly on structural traps,
however, as the basin entered a more mature phase of development, emphasis
began to shift towards unraveling the stratigraphy represented in those fields.
Rochow (1981) published the first seismic stratigraphic study of the North Sea
"Palaeogene", relating seismic units to the lithostratigraphic division of Deegan
section, incorporating seismic and well data, tied to a biostratigraphic
framework. Stewart's framework was related to tectonics by Milton et al. (1990),
expanding the idea of nested high and low frequency sea level change cycles.

Recently, a series of papers were published in a volume edited by Parker
(1993) that cover a range of time scales and stratigraphic tools. Galloway et al.
(1993) propose a tectono-stratigraphic framework for the entire Cenozoic that
displays the lowest resolution but most regional aspect of these studies.
Timbrell (1993) focuses on the Lower Eocene only and the stratigraphic
complexity of the Balder and Frigg sections. Morton et al. (1993) use heavy
mineral analysis along with biomarker stratigraphy to subdivide the section and
Vining et al. (1993) emphasize palynofacies with respect to sea level changes.
Den Hartog Jager et al. (1993) and Armentrout et al. (1993) present regional
frameworks on a scale similar to our study, emphasizing the integration of
seismic and well data. Other regional studies on this same geologic interval
focus more on seismic geometries related to tectonics (Milton and Jones, in
press) and biostratigraphic markers related to well log picks (Mudge and Bujak,
in press).
**Geologic Setting**

The Paleogene Central North Sea was part of an intracratonic seaway that covered the area occupied by the present-day North Sea and embayments up to 300 km inland of the current northern European coast (Ziegler, 1990). The basin was formed by a series of rifting events throughout the Mesozoic that were subsequently blanketed by a layer of pelagic chalks during the Upper Cretaceous. During the Paleogene, the mainland of Britain was uplifted due to a combination of rift activity tied to the spreading of the North Atlantic (Ziegler, 1990) and the development of a 'hot spot' responsible for Thulean volcanics found in the Scottish Highlands and Isle of Skye (Knox and Morton, 1988; Lewis et al., 1992). This uplift initiated deposition of clastic turbidites to the west of the Scottish Highlands into the Faeroe-Shetland Basin (Mitchell et al., 1993) and reworked chalk turbidites to the east of the Highlands into the North Sea Basin (Johnson, 1987). Following the Lower Paleocene chalk turbidites, siliciclastic submarine fans, gravity flow aprons, and extensive deltaic wedges were deposited into the Central North Sea basin during the remainder of the Paleogene. The change from chalk to siliciclastic deposition was due to the removal by erosion of chalks capping the Devonian Old Red Sandstone (Ziegler, 1990). This sandstone provenance provided a coarse-grained source area for the submarine fan reservoirs of numerous Paleogene fields. The amount of uplift based on mass balance calculations from the entire Paleogene fan section reported by Den Hartog Jager et al. (1993) is estimated to be less than 1 km.

**Paleogeographic setting**

The estimated amount of uplift in the source area has important implications in the distribution of systems tracts (Brown and Fisher, 1977, Van
Wagoner et al., 1988) within Paleogene depositional sequences. When interpreting systems tract distribution, one of the most important controls is the depositional profile or margin morphology. On the southern coast of the North Sea, intracratonic seaway ramp profiles with very low angle dips control deposition as facies relate to relative sea level changes (e.g. Plint, 1988). In the Central North Sea, a shelf-slope break developed, providing the necessary gradient (< 0.5° - Stow, 1986) to trigger turbidity currents that funnel coarse clastics to the basin during times of relative low sea level (Mitchum, 1985; Posamentier and Vail, 1988; Posamentier et al., 1991; Mutti, 1992).

On seismic profiles, it is usually easy to distinguish a single prograding deltaic unit that distally downlaps the turbidite package within each depositional sequence. This prograding package onlaps landward as it builds out into the basin, creating an extensive coastal plain. The relatively small amount of vertical uplift produced a gentle shelf gradient, creating the potential for rapid increase of shelfal accommodation space for sediment, once the prograding unit ceases to keep up with rising relative sea level. The effect of this depositional profile on sediment delivery to the basin is critical when considering a sequence stratigraphic depositional model as discussed below.

**Material and Methodology**

A 7400 km seismic grid (figure 3.1) was interpreted with approximately 100 well logs tied by synthetic seismograms supplement seismic facies analysis with geologic information. Of those wells, 40 have detailed biostratigraphic reports and are part of the 150 wells with detailed biostratigraphy that were compiled to build a North Sea composite standard from Amoco’s global composite standard. Interpretation of the biostratigraphy for individual well was accomplished by graphic correlation (Shaw, 1964; Stein et al., in press),
Fig. 3.1. - Location map of Central North Sea study area. Labeled Pre-Tertiary structural elements are: E.S.P.=East Shetland Platform, W.G.G.=Witch Ground Graben, S.V.G.=South Viking Graben, F.M.H.=Forties-Montrose High, F.A.=Fleming Area, F.G.S.=Flanden GroundSpur, H.H.=Halibut Horst & M.F.=Moray Firth Basin.
plotting data from a particular well against the composite standard of fossils for the entire basin. The construction of a composite standard and its precise application is complex. We will summarize the methodology here, but for further explanation the reader is directed to a paper by Stein et al. (in press) and the next chapter of this study, which give the details of the construction of the composite standard and its application in correlating events throughout NW Europe.

*Application and theory*

The actual construction of a composite standard is conceptually fairly straightforward. The most biostratigraphically complete, stratigraphically overlapping sections in a study area are combined to have an idealized composite standard reference section for the entire time interval being studied. By testing subsequent sections against the composite standard, stratigraphic gaps may be observed in a test section that are complete in the composite. Demonstration that stratigraphic gaps overlap in time between two or more sections establishes a framework of chronostratigraphic units. X-Y crossplots of biostratigraphic data in a well against the composite standard establish a line of correlation (LOC) for the well (figure 3.2). The LOC approximates sedimentation rate, but is actually a measure of rock accumulation through time, as resolved with the biostratigraphy (Shaw, 1964). A steeply sloping LOC indicates rapid rock accumulation in a well and a horizontal LOC demonstrates no rock accumulation in a well for some time interval. The LOC is used to place new data points in their proper relative chronological position or to emend the range of a marker carried at an incorrect position within the composite. Wells used to build the original composite are graphed against the updated composite in later iterations to determine the completeness of the original well. For this reason,
Figure 3.2. Diagrammatic graphic correlation plot of datapoints that relate first downhole occurrences of particular fossils to their youngest CSU records in the composite standard. The overall chronostratigraphic relationship of the well interval is defined by the lines of correlation (LOC). Datapoints plotting off the LOC represent occurrences in the well that are younger (Left) and older (right) than predicted by the database. The horizontal alignment of datapoints define a terrace offsetting the LOC and indicating a chronostratigraphic break (hiatus) quantifiable in terms of composite standard units, which can be calibrated to any absolute chronobiostatigraphic time scale.
subsequent rounds of correlation use the composite minus the well being graphed to avoid a circular correlation. The composite is essentially a chronological range chart for all biostratigraphic data points encountered, scaled with nonlinear composite standard units that indicate relative chronological position within the overall succession. Horizontal terraces (or terraces) in a LOC indicate missing or condensed section in a well relative to the composite and may be caused by faulting, unconformity, or nondeposition (Shaw, 1964; Miller, 1977). Graphic correlation terraces correspond to hialtal intervals (Chapters 2 & 4) in wells where core data is absent and cuttings are the primary source of information. Hialtal interval correlation is the foundation of the chronostratigraphic framework presented here.

Graphic correlation is best used in areas where outcrops or continuous core data allow the identification of faunal first appearance datums (FAD) as well as last appearances datums (LAD) or tops. This control adds an extra level of confidence in the LOC by capturing the full range of any particular taxa as originally proposed by Shaw (1964). Unfortunately, in the oil industry, economic necessity usually precludes the drilling of continuously cored wells. This practice requires that a different approach be used if graphic correlation is to be successful. In most cases, the geologist is fortunate to have a series of reported faunal tops or acmes (peak abundances), usually at 30 ft or 10 m cutting sample intervals, to construct a chronostratigraphic framework. Key bounding surfaces (unconformities, transgressive surfaces, etc.) observed in wells, outcrop and seismic data are correlated within a temporal framework to suggest a paleogeographic and depositional model.

Surface (or interval) -based stratigraphy, correlated with biostratigraphy and interpreted in terms of relative sea level fluctuations, is the essence of
sequence stratigraphy. The sequence stratigraphic model of Vail (1987) proposed a way to subdivide a section based on seismic stratal patterns and well log interpretation as they related to relative changes in sea level. This model was refined in Posamentier et al. (1988) and Posamentier and Vail (1988) to account for deposits along a depositional profile through time as a function of changing accommodation space (both on the shelf and onshore) and the response of depositional systems to fill that space. Graphic correlation has the potential to document the stratigraphic relationship of deposits along a depositional profile through time.

**Graphic correlation terraces in sequence stratigraphy**

Figure 3.3 illustrates the theoretical relationship of graphic correlation terraces within a sequence stratigraphic model of two depositional sequences. This model has been modified to reflect the separation of the highstand and transgressive shelf from lowstand basinal deposits according to the model presented below and as presented by Armentrout et al. (1993). In this idealized model, using the given relative sea level curve, biostratigraphic resolution permits the recognition of each systems tract. A well through submarine fan deposits (Well C) will have the simplest pattern of deposition with short periods of rapid sedimentation being separated by longer intervals of sediment starvation. A sequence boundary occurs at the base of each depositional package, as major fan deposition results from falls in sea level (Kolla and Macurda, 1988; Posamentier et al., 1991, Mutti, 1992). Graphic correlation terraces between depositional pulses contain the chronostratigraphic equivalent distal drape deposits of the lowstand prograding, transgressive and highstand systems tracts (time B-D).
**Sequence Stratigraphy Model (after Vail, 1987)**

- **Well A**
- **Well B**
- **Well C**

- Sequence Boundary
- Stratal time lines

**Graphic Correlation Interpretation**

*Subaerial Exposure*

Depth (Well A)

- Geologic Time

- Line of Correlation (LOC)

*Maximum Flooding Surfaces*

*Sediment Bypass*

Depth (Well B)

- Geologic Time

Sediment Starvation

Depth (Well C)

- Geologic Time

Geologic Time = Composite Standard

**Figure 3.3**: Model for the integration of graphic correlation offsets with key bounding surfaces in sequence stratigraphy. In the graphic correlation interpretation, sequence boundaries are drawn as stippled lines in time where they begin to form (i.e., with the first relative fall of sea level). The dashed LOC represents a possible brief offset at the maximum flooding surface (see text for discussion).
A well near the lowstand shelf edge (Well B) should show a similar pattern of accumulation and nondeposition as the fan setting, however, some differences are noted in the position and interpretation of LOC terraces. The first difference is the time of deposition below the first terrace. In Well C, accumulation took place between time A and B (figure 3.3). Well B accumulation extends to time C as this well encounters lowstand shelf deposits that are distally starved in Well C. The sequence boundary (time D) occurs within the LOC terrace, demonstrating a division between lack of accumulation due periods of sediment starvation and bypass. The time of bypass (time D to E) is represented by deposition above the sequence boundary in Well C. For time E to F, Well B records only the deposition of lowstand shelf sediments.

Updip wells have the most complex pattern of sediment accumulation as coastal processes of wavebase and subaerial erosion compete with variable sediment supply and sea level change. This simplified 2-D model assumes a constant deposition in the plane of section where sediment supply attempts to fill shelfal accommodation space created by relative sea level change. The solid LOC for Well A shows a single terrace, commencing with the sequence boundary (time D) and ending with renewed deposition at the next transgression (time F). This terrace reflects nondeposition due to subaerial exposure. The maximum flooding surfaces between times C-D and F-G might be associated with a small terrace (dashed line) due to a brief period of sediment starvation or wavebase erosion. Should any subaerial erosion occur, the terrace from D to F will be extended back in time to capture the time of deposition removed by this erosion. Theoretically, some instant of time is contained within a LOC terrace for wells in each setting. This instant corresponds to eroded section in Well A, the point where sediment starvation is
succeeded by sediment bypass in Well B and the time just before sedimentation resumes in Well C. If this overlap of terraces in time can be demonstrated, then a chronostratigraphic unit (depositional sequence) is documented.

Complications from nested stratigraphic cycles

Basinwide correlations must consider the effect of nested high and low frequency sea level changes. During low frequency sea level falls, high frequency falls will be enhanced and regressive pulses will occur into deeper parts of the basin. Updip sections may only encounter a single exposure surface spanning the time of a multi-sequence regression in the basin. Conversely, low frequency rises in sea level may subdue expression of high frequency falls in the deep basin while stacking thick sedimentary packages at the basin rim. These packages may record a relative sea level signal that is unresolvable in the deep basin (figure 3.4).

The graphic correlation expression of these backstepped packages depends again on biostratigraphic resolution. With a perfect resolution similar to figure 3.3, the ideal LOC of a well penetrating this section (Well A) can potentially resolve high frequency events. The relative sea level curve (figure 3.4) shows a low frequency rise with superimposed high frequency events. These high frequency cycles are of smaller magnitude than their carrier and the sediment response is of an equally smaller magnitude when compared to the regressive wedge penetrated by Well B (figures 3.3 & 3.4). The smaller events cause a period of subaerial exposure similar to larger falls, however, deposition during relative lowstand of sea level is restricted to the inherited shelf. Little, if any, sediment reaches the shelf-slope break. This is caused by an excess of shelfal accommodation space that the sediment flux from sea level falls at $c'$ and $c''$ cannot fill.
Figure 3.4. Possible complications in the resolution and correlation of events when deposits from a high frequency sea level signal are preserved on a low frequency sea level rise. High frequency events are correlated within low frequency cycles except where sediment supply or data resolution allows for their separation.
Although smaller in magnitude, deposition during this sea level cycle has all the characteristics necessary for a depositional sequence and should be identified as such (Mitchum and Van Wagoner, 1991). Given perfect preservation and biostratigraphic resolution, the LOC for a well through this section will record small terraces, caused by the brief period of subaerial exposure (fig. 3.4-time following c' and c"). A more distal well (Well B) may only recognize the low frequency signal, illustrating the need for careful correlation of events to avoid mistying high frequency surfaces to low frequency deposits. Line of correlation terraces that overlap in time fulfill one of the necessary requirements for a documented chronostratigraphic framework, but they do not exclude the possibility of additional events that are below resolution.

**Stratigraphic Correlations and Depositional Model**

Depositional sequences observed from Central North Sea subsurface data have been given lithostratigraphic names from the lithostratigraphic frameworks of Deegan and Scull (1977), Isaksen and Tonstad (1989), Mudge and Copestake (1992), and the Paleo-Services/Chevron framework of the Mid-Upper Eocene (Newton and Flanagan, 1993). These sequences are distinguishable with biostratigraphy and physical stratigraphy. They do not represent all the sequence cycles recorded in the North Sea basin. More sequences have been observed in outcrop from northwest European basins (Chapter 4), but are not recognized within the resolution of the subsurface data base. The complete sequence stratigraphic framework for the Paleogene of Northwest Europe will be presented and discussed below.

Figure 3.5 illustrates the correlation of depositional sequences used in the Paleocene to Lower Eocene section to lithostratigraphic units from type wells of Mudge and Copestake's (1992) and Isaksen and Tonstad's (1987)
Figure 3.5. Correlation of depositional sequences, key biostratigraphic markers, and hialtal intervals with namesake lithostratigraphic units from recently published frameworks. Abbreviations for lithostratigraphic units: E=EkoFisk Fm., M=Maureen Fm., A=Andrew mbr., G=Glamis mbr., B=Balmer Fm., L=Lista Fm, S=Sele Fm., F=Forties mbr., D=Dornoch mbr., Be=Beauly Fm., B=Balder Fm., Fg=Frigg Fm., Hr=Hermod Fm., Hm=Heimdal Fm. Also shown are Stewart’s (1987) sequences: S = type section for the sequence (see text for discussion).
frameworks. Also displayed here is a correlation to depositional sequences published by Stewart (1987), using his well sections and maps as tie points. The diachronality of Stewart’s (1987) sequences illustrates the need for a framework, founded on biostratigraphy, then tied to wells and seismic.

The depositional sequences of this study do not always correlate with their lithostratigraphic equivalents. Sequences are identified by their biostratigraphy and position on a graphic correlation LOC, related to surfaces on seismic and logs. As such, they are chronostratigraphic units and the same sequence may contain more than one lithostratigraphic unit. Correlation of lithostratigraphy with sequence stratigraphy must be done with extreme caution. Lithostratigraphy is based on objective criteria with strict rules of application (e.g. Whittaker et al., 1991). Describing a type log signature for any sequence is problematic as illustrated by the “Upper Sele” sequence. This sequence typically has acme occurrences of the dinocysts, *Cerodinium wardenense* at its base and *Deflandrea oebisfeldensis* at its top. This sequence is often also associated with a downhole influx of large leiospheres, however, an acme occurrence of *Pterospermella*, grouped with the leiospheres influx by Knox and Holloway (1992), is found in an older sequence. In type wells for each lithostratigraphic framework, the Upper Sele sequence markers may be found together or separated, in the Balder Formation (tuffaceous claystone), Sele Formation (dark grey clay), Hermod Formation (deep water sandstone), or in their shelfal equivalent Beauly Formation.

A 30 m “error bar” between the reported fossil depth occurrence and the well log pick was used by Armentrout et al. (1993), to account for operator consistency and seismic resolution. Using this margin of error allows great freedom in making a sequence pick fit the data. Generally, we tried to achieve
precise agreement between at least two of the three disciplines used in this study (log interpretation, paleontology, and seismic interpretation). The error bar mentioned by Armentrout *et al.* (1993) is one way to reconcile a mistle of biostratigraphy with well log and seismic interpretation. When sequences are below seismic resolution or occur within a seismically chaotic zone, well log interpretation and fossils are the only tools that allow correlation with any confidence.

Sequences are picked on individual well logs based on an interpretation of the relative sea level signal for each particular location, correlated with biostratigraphy. For example, in deep water settings, the base of the Upper Sele sequence occurs at a high gamma marker on electric logs near the reported acme occurrence of *C. wardenense* from cuttings. The sequence boundary is interpreted to be combined with the underlying maximum flooding surface. The sequence boundary marks renewed basinal deposition due to a fall in relative sea level and shelfal bypass (figure 3.3), depositing sediment containing abundant *C. wardenense*, capped by hemipelagic drape containing abundant *D. oebisfeldensis*. In shelfal settings, the sequence boundary occurs at the base of a thick coal, an incised valley deposit, or at the base of a transgressive sandstone. These deposits may overlie a high gamma shaly section interpreted to represent periods where sediment is ponded in a coastal system to the west. The coal represents the remains of a marsh and a base level zero datum (Milton *et al.*, 1990). Thick, rooted coals are indicators of transgression (Cross, 1988; Milton *et al.*, 1990), therefore, their bases are likely exposure surfaces. Not all coals overlie sequence boundaries, however, as the Balder sequence (Beauly Formation) contains many coals that are discontinuous and simply reflect delta lobe abandonment within an overall transgressive package.
Well examples of graphic correlation using the composite standard

The composite standard for the Central North Sea has been largely built and utilized in the deep marine environment where correlation of turbidite packages relies on good biostratigraphy. A sequence stratigraphic interpretation involves a series of steps that begins with interpretation of the biostratigraphic data, followed by picking sequences on the well logs that are tied to seismic with synthetic seismograms, and finally correlated with seismic between well control points. Construction of a composite standard begins with a search through the data set for sections that appear to have the most complete biostratigraphic succession. The best section serves as a reference section for the basin. In this study, the Norwegian well, N16/1-1 (figure 3.6) was chosen based on the fact that it contained a nearly complete succession of biostratigraphic zones used in the well report by Robertson Research International (data in Appendix Table 1). Starting with a single LOC terrace from a sample at 7260 ft, this well is now shown (figure 3.6) to contain 9 to possibly 11 LOC terraces resulting from iterative rounds of graphic correlation (Stein et al., in press).

The sequence stratigraphic interpretation of this well follows from the model described in figure 3.3 (Well C). The paleobathymetry estimates for samples from this well never get shallower than upper bathyal and the LOC terraces represent sediment starvation and possibly submarine erosion. The solid LOC (figure 3.6) represents a graphic correlation based on biostratigraphic markers that regularly occur in proper succession. These markers include the first downhole occurrence (FDO) of Globorotalia pseudobulloides, Globorotalia compressa, and the acme occurrence of Areoligera cf. senonensis sensu RRI. (now gippingensis). The stippled LOC
Figure 3.6. Graphic correlation and sequence stratigraphic interpretations of a key basinal well. Biostratigraphic data is courtesy of Simon Petroleum Technologies (Robertson Research) with numbered tops listed in Appendix Table 1. Lithology key: ⬇️=shale,➡️=sand,➡️➡️=silt,➡️➡️➡️=tuff,➡️➡️➡️➡️=limestone.
highlights some possible departures from the solid line where sequence stratigraphic analysis of the well log suggests alternative terraces. The base of the Andrew sequence is picked at the base of a limestone at 8680 ft well depth. A FDO of *Alisocysta reticulata* occurs near this contact. Although the well report indicates the occurrence to be reworked, it appears to fall in proper succession (on the LOC). A series of markers starting with *Isabelidinium? viborgense* at 8550 ft seem to define a line segment up to the acme occurrence of *Palaeoperidinium pyrophorum* at 8300 ft. In order for this segment to represent the true LOC, a cluster of data points at 8400 ft containing *G. pseudobulloides* and *G. compressa* must be ignored as reworked and the well report does question whether these markers are indeed *in situ*. Unfortunately, this well is not tied to seismic in our data set, so support for either interpretation remains absent.

Another departure from the solid LOC is observed at 7860 ft, where the base of the Upper Balmoral sequence is picked at the base of a 200 ft thick sand. The regional hiatus between the Upper and Lower Balmoral sequences is usually associated with the acme of *A. cf. senonensis (gippingensis)*, however, that marker is picked in a cored interval within the Lower Balmoral sand and the solid LOC reflects that control point. The stippled LOC honors a FDO of *Pseudobolvina* sp. 1 RRI that normally occurs within the Lower Balmoral sequence and terraces over to the solid LOC controlled by markers such as *Alisocysta margarita* and the reappearances downhole of agglutinated foraminifera like *Spiroplectammina spectabilis* and *Rhizammina/Bathysiphon* in the Paleocene. These departures illustrate the strength of a checks and balances system between the sequence stratigraphic and graphic correlation
interpretations. The true test of a correlation comes with a tie to seismic using synthetic seismograms.

**Shelfal Interpretation**

A different depositional setting is considered in the next example as shelfal environments are encountered. Figure 3.7 shows the gamma curve, lithology, graphic correlation and sequence stratigraphic interpretation of a well through the Upper Paleocene shelf. Critical to the interpretation of this section is the paleobathymetry column estimating the depositional environments of these sediments using benthic forams and other indicators. Sequence and systems tract picks come from well log interpretation of depositional environment (Vail, 1987; Vail and Wornardt, 1990) and basinward shifts in facies, however, log patterns alone are not diagnostic. For example, the sand at a depth of 3500 ft has a log pattern similar to other sands below 4600 ft. Paleobathymetry estimates places the upper sand in the transitional marine to inner shelf environment while the lower sands were deposited in an upper bathyal water depth. The lower sands represent fan deposition during falling sea level and the upper sand is interpreted as incised valley fill during rising sea level. The paleobathymetry alone can track low frequency sea level cycles with peak floodings around 4500 ft and 2700 ft..

The LOC for this well has few terraces, but they provide some interesting information. The first observation is that more sequences are identified on the well log than are reflected in the LOC. Sequences are correlated within LOC terrace-bounded units. This problem was discussed above and requires regional work to document sequences picked on physical surface criteria (wells and seismic—see below). Another point is made by the terrace at approximately 3700 ft depth, which corresponds to a high gamma marker interpreted to be a
Figure 3.7. Sequence stratigraphic interpretation of a well with shallow water section. Systems tract interpretations are based on log character and paleobathymetry: LLST=lower lowstand (bypass sediments), ULST=upper lowstand (lowstand prograding and slumps), TST=transgressive systems tract, IVF=incised valley fill, HST=highstand systems tract. Paleobathymetry courtesy of S.P.T. (Robertson Research). Lithology: 🅿️=limestone, 🅷️=marl, 🅹️=sand, 🅱️=silt, 🅱️=shale.
maximum flooding surface. In this case, the terrace may be caused by starvation or wavebase erosion (e.g. Well A, figure 3.3). Another possibility is that environmental conditions caused an terrace to form here because water depths for overlying deposits are very shallow, with samples containing only pollen and spores. With this real data set, resolution of the type described in theoretical models above is not achieved. The terrace in the shelf well overlaps with similar terraces found in distal wells. Clearly the mechanism for the formation of an terrace in the shelf well will differ from basinal ones, however, if terraces in each location contain similar fossils, they will necessarily occupy the same time. The ideal should be considered, but reality controls the actual data. It is up to the interpreter to realize and communicate these limitations. This does not invalidate the chronostratigraphic correlation, it simply requires an awareness of the resolution limits.

The "terrace" across the Lower Eocene section in this well highlights another limitation, which is data sampling. The LOC has a gradual slope as dictated by the data, however, paleobathymetry estimates note a rapid deepening above 2900 ft. The sand between 2900 ft -2700 ft is interpreted as a lower lowstand deposit, due to the upper bathyal water depth estimate. A possible explanation for the scatter of data points is that rapid deepening occurred above the section deposited at 2900 ft. A great deal of time may be represented in deposits below the Lower Eocene sand, but the sand was deposited by gravity flow processes that reworked fossils from the underlying "condensed section".

This unit highlights why "hiatal interval" terminology is preferred over "condensed section" (Loutit et al., 1988). The Lower Eocene sand was probably deposited rapidly, despite the gradual slope of the LOC. Most of the time for this
interval is likely represented in section above and below the sand, however, sampling resolution is unable to verify this. The Lower Eocene spans 5 Ma according to Haq et al. (1988). If the sand is assumed to be deposited by turbidite events, then most of that 5 Ma must be accounted for in the very thin high gamma shales above and below this unit. Sedimentation rates necessary to accommodate this amount of time in such thin units are well under 1 cm/ky, unrealistically low for an intracratonic basin such as the North Sea without accounting for periods of erosion (Sadler, 1981). Since hiatuses are difficult to recognize from electric logs, the conservative interpretation would be to recognize that hiatuses occur in this section without directly determining their exact location.

Shelfal sections often have problematic LOCs when using a composite standard built mainly from basinal wells. The advantage shelfal wells have over their distal counterparts is that deposits resulting from sea level changes are more easily distinguished from autocyclic deposits. In the basin, sea level changes are determined indirectly by recognizing sediment pulses as resulting from sea level fall and linking drape deposits to periods of high sea level. Without good chronostratigraphic control, any rapid increase in sedimentation rate might be mistaken for a separate depositional sequence when, in fact, it could result from fan lobe avulsion. In shallow sections, basinward shifts of facies are the clearest indicator of sea level change. Shelfal sections, if thick enough, also display seismic stratigraphic patterns that relate to changes in sea level (figure 3.3). The correlation of wells to seismic in a shelfal setting can provide additional support for sequences that may be biostratigraphically unresolvable.
Seismic correlation

Sequences picked on less than convincing evidence in one well may be verified by correlation to neighboring wells and seismic data (figure 3.8). Sequences constrained between LOC terraces may or may not have exactly the same time of intercept with the LOC between terraces. The Middle and Upper Sele sequences show this relationship when correlating between wells 15/6-1 and 15/13-2. These two wells have been interpreted for depositional sequences and tied to seismic with synthetics. The Sele sequences are picked at physical surfaces in the wells and on seismic (figure 3.8). In the 15/6-1 well, both sequence boundaries are picked at the base of transgressive sands, indicated by upward increasing gamma values. The Upper Sele sequence has highstand progradation (see figure 3.7) that rapidly thin towards the shelf break (figure 3.8). In well 15/13-2, a slope sand body rests on the Middle Sele sequence boundary and the sand is capped with mudstone equivalents of updip transgressive and highstand deposits. A carbonate layer marks the Upper Sele sequence in this well. This bed may represent a hardground omission surface that is unresolvable with biostratigraphy with the overlying silty section interpreted as lowstand deposits. These sequences fall between two overlapping terraces, but do not intersect the LOC at precisely the same time. They are chronostratigraphic units nonetheless, as demonstrated on seismic data.

The LOC for 15/13-2 distinguishes terraces in the Lower Eocene section (Frigg Undif.) that are not apparent in 15/6-1. The Frigg Undif. section has been subdivided into at least three separate sequences (discussed below), and the LOC for 15/13-2 hints that this is possible. Correlation with LOC terraces provides some information on the chronostratigraphic equivalence of the
Figure 3.8. Correlation of depositional sequences in a shelfal setting by well log and seismic interpretation and graphic correlation. Lithostratigraphic units are from Robertson Research. Lithology key is: \[\text{---------} = \text{sand}, \text{-----} = \text{silt}, \text{-----} = \text{shale}, \text{-----} = \text{carbonate}\]. Seismic data is courtesy S.P.T. (Horizon Geophysical).
"Dornoch" deltaic lithostratigraphic unit, which is apparent on seismic data. This correlation suggests that the lower prograding unit of the Dornoch in 15/6-1 (~4000 ft - 3600 ft) falls within a different chronostratigraphic unit the lower prograding of 15/13-2 (~1560 m - 1410 m). Tying well picks to seismic confirms this correlation as a deeply incisive sequence boundary separates the overall prograding package into two distinct units. As a side note, this section also supports the interpretation of these prograding units as lowstand since the base of the incisive canyon occurs at the same depth as the first toplap (Mitchum et al., 1977) in the eastern prograding package. Toplapses in deltaic units are considered to represent baselevel in true dip sections (Mitchum et al., 1977, Milton and Jones, in press), and by calculating from seismic conversion the depth at the top of a prograding package to the depth of the first toplap in a subsequent progradation, a minimum estimate of sea level fall is obtained. The physical relationship of deposits in this example (figure 3.8) suggests that sea level fell at least 150 m.

Central North Sea Paleogene depositional model

A notable feature of the depositional sequences seen in the previous examples is the lack of significant transgressive and highstand systems tract deposition. This situation is consistent with published models (Vail, 1987; Posamentier et al., 1991) for the bathyal environment, seen in figure 3.6. However, the shelfal deposits of the UK15/6-1 well (figure 3.7) show only minor transgressive and highstand systems tracts, which rapidly thin basinward to below seismic resolution (figure 3.8). Explaining this situation requires a variation of the Vail-Exxon sequence stratigraphic depositional model similar to the one proposed by Armentrout et al. (1993), where transgressive and highstand deposits are landward of the lowstand shelf break.
Depositional sequences in the study area consist mainly of a shelfal bypass package and a prograding deltaic package. The delta downlaps directly onto the bypass sediments at the base of the slope. In deeper parts of the basin, bypass packages are separated by thin hemipelagic muds where biostratigraphic hiatal intervals are expected and observed (figures 3.3 & 3.6). These hiatal intervals have been shown to correlate with shelfal deposits in Northwest Europe, suggesting a partitioning of sediments between the shelf and deep basin tied to relative sea level changes (Chapters 2 & 4). The depositional model presented here considers the effect of the depositional profile on shelfal accommodation space and changing sediment supply as relative sea level changes.

**Highstand or lowstand prograding**

Highstand progradation occurs as relative sea level rise decreases. The coastline regresses due to sediment influx filling shelfal accommodation space faster than it is created (Jervey, 1988; Posamentier et al., 1988). Theoretically, parasequence stacking patterns and clinoform geometries will be aggradational to progradational (Van Wagoner et al., 1990). In North Sea well data, this situation is difficult to observe. However, downlap onto the maximum flooding surface should be apparent with the maximum flooding surface capping all lowstand deposits. In North Sea data, the clearest downlap surface comes directly over the bypass package, below the prograding delta. This presents three possible systems tract interpretations for this section: (1) the prograding delta is highstand progradation and the lowstand delta is thin or absent (e.g. Vining et al., 1993), (2) the prograding package represents the lowstand prograding, transgressive and highstand systems tracts combined due to overpowering sediment supply from the uplift of the British mainland (e.g. Milton
and Jones, in press), or (3) the prograding is a lowstand delta with transgressive and highstand deposits thin or absent in this location.

We interpret the prograding packages to be lowstand based on their internal stratal patterns, relationship to canyon incision (see figure 3.8), the presence of hialtal intervals on the shelf and well log interpretation indicating deepening over the progradation. With this interpretation, a depositional model through one cycle of sea level change is illustrated in figure 3.9 (A-D).

**Deposition through a cycle of relative sea level change**

Identifying highstand deposits is difficult due to uplift and erosion of older sequences into younger deposits. The diagram of a highstand shelf is hypothetical (figure 3.9A), and considers the effect of a reduced sediment source area in the production of sediment and its delivery to the coast. The main source area for North Sea Paleogene deposits is the Scottish Highlands (Ziegler, 1990) with an estimated 1 km of uplift (Den Hartog Jager, et al., 1993). This area is small compared with adjacent basins to the west (Rockall-Faeroe) and east (North Sea). Present-day highstand deltas are building out onto extensive shelves in the Gulf of Mexico (Hamilton and Anderson, 1993) and Mediterranean Sea (Rhone delta-Posamentier et al., 1992b). These deltas have large sediment source areas compared to the Scottish Highlands, which split its potential sediment between two basins. Therefore, sediment supply during highstand periods in the Central North Sea is believed to be low.

When sea level begins to fall in this setting, conditions exist for "forced regression" deposits to appear according to Posamentier et al. (1992b). Galloway et al. (1993, p. 38) describe shelf erosion and bypass unconformities in the North Sea following a model proposed by Plint (1988), where wave base erosion removes potential "forced regression" deposits as sea level falls. The
Figure 9 (A-D). Block diagram of deposition in the Paleogene Central North Sea through one cycle of relative sea level change. The facies distribution is modelled after the Upper Forties Sequence, however, no exact scale is given (see text for further discussion). Paleogene facies key: ☐ = coastal sand, ■ = prodelta mud, □ = sandy turbidites, ☏ = Danian chalk, ◮ = hemipelagic mudstone.
B. Relative Fall (Lower Lowstand Systems Tract)
C. Increasing Relative Sea Level Rise - Upper Lowstand Systems Tract (lowstand prograding)
D. Rapid Rise (Transgressive Systems Tract)
North Sea depositional profile acts like a ramp on the shelf, but rapidly deepens across a shelf edge with slopes of 5-7°. Sediments swept from the shelf during a fall in sea level pass into the basin as turbidites (figure 9B), forming sandy fans (point source) or gravity flow aprons (line source). Sediment shed from the source area is added to sediment ponded in the highstand coastal zone, increasing the total sediment input to the basin and shelf.

The shelfal bypass sediments come into the basin through the fall of sea level into its early rise. The early rise of sea level marks the first re-establishment of a lowstand shelf, however, this shelf is unstable and prone to slumping due to the steep slope inherited from the previous depositional sequence. The effect of this slumping and the bypass fill of the slope front is to reduce the profile gradient enough to allow stable progradation to occur. The delta will build out as long as sediment flux into the basin is greater than the rate at which shelfal accommodation space is created due to increasing relative sea level rise (Posamentier et al., 1988). As the rate of relative sea level rise comes into equilibrium with sediment flux, the delta will aggrade. During this aggradation, the lowstand coastal plain will onlap landward and broaden (figure 9C).

This broad, flat coastal plain creates the potential for a rapid transgression once the rate of relative rise exceeds sediment flux. A small sea level rise pushes the coastline far landward, lowering sediment supply to the shelf (figure 9D). Once flooded, the shelf may be swept by fairweather wave base (Plint, 1988) explaining the lack of thick transgressive and highstand deposits. In the basin, hemipelagic drape deposition and submarine erosion processes interact to produce the hialtal intervals described above.
Stratigraphic Cycles and Depositional Systems of the Paleogene

This study documents five second order cycles, the lower four corresponding to similar units mentioned by Den Hartog Jager et al. (1993, p. 61). Overprinting third-order depositional sequences are also documented and regionally correlated. These cycles are recognized from their physical expression in the rocks rather than their absolute time duration (sensu Vail et al., 1991). How our cycles compare with published results of other studies will be discussed below.

Third order cycles produce depositional sequences described in the above depositional model and may or may not be associated with a resolvable hiatal interval. They reflect a higher order sea level change that controls distribution of depositional systems and lithofacies. Third-order cycles produce depositional sequences whose characteristics are linked to where the cycle falls within a second-order cycle. Third-order cycles may be eustatic, however, they have only been documented to be correlative for the Central North Sea Basin and its attached embayments of Northwest Europe (Chapter 4).

Second-order cycles reflect major reorganizations of depositional systems and are bracketed by major hiatal intervals. They contain multiple depositional sequences that are best resolved during the regressive phase. Second-order cycles have different magnitudes and are believed to reflect periods of uplift and subsidence of the basin rim and sediment source areas.

Order in stratigraphic cycles has been formally defined in Vail et al. (1991), with second order cycles lasting 3 - 50 My, third order cycles ranging from 0.5 - 3 My, and fourth order cycles covering a range of 0.08 - 0.5 My. The stratigraphic cycles of this study appear to fall within all three orders. The relationship of various order cycles has developed from the classical
discussions by Sloss (1963) and Vail et al. (1977). Implicit in the present debate on cycle order is the recognition of significant differences between the orders of cycles. This is the concept of stratigraphic signatures (eustatic, tectonic, and sediment supply) in basin analysis, which attempts to differentiate cycles based on their sedimentation characteristics and duration (Vail et al., 1991). This idea has been greatly aided by computer models that control input parameters of uplift, subsidence, sediment supply, and eustasy within a two-dimensional section. However, the recognition, quantification, and distinction of these parameters in seismic data remains difficult, if not impossible. What remains are the pure observations from the data. In Paleogene North Sea deposits, similarities in the distribution of facies within cycles of each duration are noted. Differences are observed in the map distribution and divisibility of cycles within the resolution of the database. Graphic correlation makes an invaluable contribution to this problem by quantifying relative amounts of time represented by the various hialtal intervals and, although an exact absolute age calibration of these cycles is not presented, their relative duration can be seen.

**Nested cycles expressed in well and seismic data**

An example displaying the nesting and similarities of second- and third-order cycles is seen from seismic in figures 3.10 and 3.11 and in well log cross section from figure 3.12. The Lower Paleocene regression occurs in this section as sandy turbidites in bathyal paleowater depths. A Lower Paleocene shelf occurs 20 km to the west of this section. The regressive phase of the Upper Paleocene cycle forms a multi-sequence shelf that progrades far into the basin. Depositional sequence picks are based on interpreted basinward shifts of facies from well logs, tied to mappable seismic discontinuities with synthetic seismograms. Above the rapid progradation occurs a high amplitude seismic
Figure 3.10. Seismic section through the Witch Ground Graben (see figure 1 for location) displaying the major second order cycles of the North Sea Paleogene. The characteristic cycle of bypass, prograding and transgressing occurs at different scales, showing how stratigraphic cycles nest within each other. Deciding on a hierarchy of cycles is critical to stratigraphic analysis of an entire basin (see text for discussion). Well 14/20-22 is a tie point between observations at this scale and higher resolution scales in the next figures. Seismic is courtesy S.P.T. (Horizon Geophysical).
Fig. 3.11. Seismic expression of the mid-Lower Eocene regressive shelf. Labeled features are: A. Upper Balmoral sequence, B. Upper Forties sequence, C. Middle Sele sequence, D. Upper Sele sequence, E. Main Balder sequence, F. Frigg Regression (undifferentiated), G. Nauchlan sequence, H. Lower Lark 1 sequence. Stratal terminations are highlighted with small arrows. Note the backstepping units within the Balder sequence separated by a transgressive surface (dashed line). Third order boundaries = ——— , second order boundaries = ———. Seismic data is shown courtesy of SPT (Horizon Geophysical).
Fig. 3.12. - Stratigraphic cross section through the Witch Ground Graben area of the Central North Sea (see Fig. 3.1 for location). A composite graphic correlation display of three of the five logs with detailed biostratigraphic reports highlights the second order transgressions that bracket multi-sequence regressive pulses. Paleobathymetry of the Lower Paleocene pulse is bathyal, while the Upper Paleocene shallows to inner shelf and transitional. The next two regressions are deposited in outer shelf/upper bathyal depths, with UK 15/6-1 having an inner shelf Upper Middle Eocene section (see text for discussion). Paleobathymetry estimates are from S.P.T. (Robertson Research).
interval (figures 3.10 & 3.11), interpreted as coaly coastal plain section that aggrades rather than progrades. This section also has more than one depositional sequence. The depositional systems are responding to a turnaround in the second order cycle and the lithofacies are characteristic of a transgressive system of stacked coals (Cross, 1988; Milton et al., 1990) rather than the regressive characteristic of rapidly prograding deltas. Above the coaly section is a throughgoing seismic reflector that can be traced to wells with biostratigraphic reports where a hiatal interval is observed (figure 3.11). This reflector drapes over topographic relief in the coaly section. Milton et al. (1990) interpret topographic relief in top coal reflector to represent differential compaction of the underlying strata. The mudstone drape and compaction sag represent a period of quiescence in the basin.

The next regression marks another second-order cycle of lesser magnitude than its predecessor. The small prograding unit downlapping the draping seismic reflector does not reach the previous shelf edge but is more extensive further north (Timbrell, 1993). This regression is importance as it produces the submarine Frigg fan with 7 Tcf of gas in place (Heritier et al., 1980). The top of this regressive unit is traced to wells that display another major hiatal interval (figure 3.11). The top of this unit is a basinwide downlap surface that marks a period of quiescence before the next second-order regression rapidly progrades.

The Mid-to-Upper Eocene regression is very sandy and thick in this location. It has been linked to renewed uplift in the Shetland Platform (Milton, and Jones, in press; Galloway et al., 1993). Graphic correlation indicates that this unit was deposited very rapidly and is capped by one of the longest hiatal intervals in the section (figure 3.11). This peculiar boundary will be discussed
below, but for now it will simply be described as a stratigraphic break between the Mid-to-Upper Eocene cycle and the overlying Lower Oligocene cycle that thickens to the east. The top of the Lower Oligocene section is a major flooding that signals another reorganization of the basin with subsequent cycles having a larger input from Norway (Michelsen et al., in press; Galloway et al., 1993).

These examples illustrate how higher order cycles can be recognized as data resolution and stratigraphic observations improve. Milton and Jones (in press) have interpreted the Paleogene section as comprising only two second order cycles. Figure 3.10 shows how a two-fold division of this section can be easily observed. The sedimentation cycle of bypass, progradation and transgression occurs at a minimum of three different time scales within this example alone. Each cycle can be subsequently split into additional divisions with the sole limiting factor being data resolution. As the time scale for cycles grows shorter, the list of mechanisms that may have caused it changes (Van Wagoner et al., 1991). Once division is at the scale where autocyclic processes dominate, then the basin-wide correlative nature of events becomes suspect. We have settled for a division of events in the fourth to third order (sensu Vail et al., 1991), which we lump as third order, superimposed on second order cycles of approximately 3-13 My.

**Lower Paleocene cycle**

The Lower Paleocene second-order cycle formed in response to uplift and tilting of the Scottish Highlands and Shetland Platform (Parker, 1975; Stewart, 1987; Milton et al., 1990). It begins with the Cretaceous/Tertiary boundary in this study, although evidence from chalk reworking events suggests that uplift began in the Upper Cretaceous (Kennedy, 1987). The upper boundary of this cycle is a hiatal interval associated with an acme occurrence of
A. gippingensis. O'Connor and Walker (1993) discuss how this biostratigraphic marker relates to the lithostratigraphic divisions of Lista and Sele Formations (Mudge and Copestake, 1992), finding that it occurs in the upper portion of the Lista, not precisely at the Lista/Sele boundary (see figure 3.5). This interval was recognized by Stewart (1987) as a second transgressive phase within the Paleocene, although the precise pick varied (figure 3.5 - Sequence 6). Subsequent revisions of Stewart's (1987) framework (Milton et al., 1990; Milton and Jones, in press) have recognized only one major regressive phase in the Paleocene, comprising the Andrew and Forties cycles of Den Hartog Jager et al. (1993), which approximate the Lower and Upper Paleocene cycles of this study.

The Lower Paleocene second-order regression may be subdivided into four (and possibly five) third-order depositional sequences (figure 3.5). Biostratigraphic correlation of the upper boundary hiatus interval to northwest Europe identifies an extra sequence not resolved in the study area (Chapter 4). The Ekofisk sequence may comprise two sequences, although this division is are difficult to distinguish where Ekofisk sands do not occur. These two sequences are thickest in the study area over pre-existing Mesozoic grabens that had not filled with Cretaceous chalk. In these localities, the sequences may be identified seismically, but outside of the depocenters it is often difficult to distinguish top Cretaceous from top Chalk.

Above the chalk, siliciclastics come into the basin as uplift continues and erosion progresses down to Devonian sandstones (Ziegler, 1990). Figure 3.13 illustrates the distribution of clastic fans and seismic expression of the Lower Paleocene peak regressive shelf in the Moray Firth area from a seismic line published by Milton and Jones (in press). The Maureen sequence fills in the
Figure 3.13: Map and seismic expression of the Lower Paleocene regressive sequence. Seismic reinterpreted from Milton and Jones (in press).
Eocene deposits

(location of seismic
and Jones, in press)

Maureen
turbidites
bypass to
Fleming area

Andrew Sequence
Maureen Sequence
Ekofisk Undiff.
K/T boundary

Balder-Frigg Undiff.
L. Oligocene Reg.
M.-U. Eocene Reg.
U. Paleocene Reg.
L. Balmoral Sequence

10 km

The regressive shelf and bypass units.
Moray Firth Basin with a wedge of sediment that has dip slopes of $2^\circ$-$3^\circ$. Locally, mounded fan deposits occur at the eastern edge of UK Quad 13 (figure 3.13). Further east, this sequence becomes thin and marly with occasional blocks of chalk debris until reaching the eastern edge of the junction between the South Viking and Central Grabens (Fleming area). Here, locally well-developed sandy fans are found. If the source area was restricted to northern Britain, these sands bypassed almost 140 km of basin floor before being deposited against submarine topography according to the onlap model proposed by Scott and Tillman (1981). Maintaining a turbidity current requires a slope of at least $0.5^\circ$ (Stow, 1986), which fits Rochow's (1981) observation of basin floor tilting and deepening in response to uplift of the Shetland Platform.

Thulean volcanics in western Scotland result from 'hot spot' activity of a plume presently situated under Iceland (White, 1988). The peak volcanic activity occurred around 60 Ma (Musset et al., 1988), which coincides with peak uplift of northern England from fission tract analysis (Green, 1989). The timing of this peak uplift correlates with the base of the Andrew sequence from biostratigraphic ties. The Andrew sequence has a more extensive fan system than the Maureen sequence (figure 3.13), which reflects this peak uplift and erosion of more clastic sources. The Andrew sequence has a thick prograding wedge that is heavily eroded at its top. This upper sequence boundary accentuates the shelf break where dips have been calculated from seismic to approach $10^\circ$, which may result from slump scars.

Onlapping the top Andrew sequence boundary is the Lower Balmoral sequence (figure 3.13). This sequence contains sandy turbidites throughout the study area and is the thickest and most widespread unit in the Paleocene. It does not, however, possess an extensive prograding package that probably
relates to a collapse of the Lower Paleocene uplift phase. The base of this sequence is associated with an acme occurrence of the dinocyst, *P. pyrophorum*, and the FDO of the radiolarian, *Cenodiscus* (figure 3.5). This unit was identified as Sequence 3 by Stewart (1987), but Figure 3.13 shows the distribution of the underlying Andrew fan, which closely resembles a map for Stewart's Sequence 5 (1987- his figure 11). The relationship of our sequences to Stewart's is illustrated in figure 3.5.

**Balmoral tuffite/Glamis Member**

Within the Lower Balmoral sequence are found volcanioclastic sands ascribed to a phase of eruption in the Thulean provenance (Knox and Morton, 1988). These sands are found in the Outer Moray Firth area and have been designated the Glamis Member of the Lista Formation by Mudge and Copestake (1992). The Glamis Member has been designated as a separate depositional sequence in some sequence stratigraphic frameworks of this section (Stewart, 1987; Milton *et al.*, 1990). The low gamma ray response and high sonic velocities make this unit stand out in well logs and on seismic sections. Biostratigraphically, this unit is age-equivalent with Lower Balmoral sediments that do not contain the volcanics (i.e. above the acme of *P. pyrophorum* and LAD of *Cenodiscus* and below the acme of *A. gippingensis*). Seismically, the tuff reflector is discontinuous and appears to form large, laterally onlapping lobes (figure 3.14). Picking the base of a single lobe as a sequence boundary may correlate to the top of a different lobe. We agree with Knox and Holloway (1992) that this unit should be recognized for its stratigraphic position, but that it does not constitute a separate sequence.
Figure 3.14. Seismic expression of the lobate nature of Glamis Member volcanic sands. The sequence boundary (SB) at the base of this package separates the Andrew sequence from the Lower Balmoral sequence. Seismic data courtesy of GECO-Prakla and Nopec.
**Upper Paleocene cycle**

The Upper Paleocene to Lowermost Eocene sediments record the best developed second order cycle in the study area. Nearly complete third order sequences are found with well-developed fans, prograding deltas, and even some transgressive and highstand deposits. This second order cycle also contains the Lista/Sele Formation boundary that marks a time of oxygen-depleted bottom water conditions thought to be related to an isolation of this basin from open marine circulation due to tectonic uplift (O'Connor and Walker, 1993; Knox and Holloway, 1992). The upper sequence in the Upper Paleocene cycle contains tuffaceous claystones of the Balder Formation, found throughout Northwest Europe and linked to explosive volcanism in the Thulean provenance that has been timed with the collapse of the Paleocene uplift of Scotland (Knox and Morton, 1988; Milton et al., 1990; Knox and Harland, 1979).

The oldest third order sequence of this cycle is the Upper Balmoral sequence, so named because it coincides with the Balmoral Member of Mudge and Copestake (1992) in well 21/10-1, but is younger than the same lithostratigraphic unit in wells 14/25-1 and 15/26-1 (figure 3.5). This sequence occurs above a hiatal interval that often contains the acme of *A. gippingensis*, with its upper boundary near the reappearance downhole of agglutinated forams, namely *Rhizammina/Bathysiphon* (M5 of Mudge and Copestake, 1992). This sequence also contains the FDO of *Areoligera margarita*, which is a common marker throughout northwest Europe. In regional maps, the thickest fan packages of this sequence are deposited in areas where the Lower Balmoral is thin, suggesting the possibility of differential compaction topography control on sandy fan distribution.
The Upper Balmoral sequence contains a deltaic package, which has been included in the Dornoch lithostratigraphic unit by Knox and Holloway (1992). The best example of this correlation is that of wells 15/6-1 and 15/13-1 (Knox and Holloway, 1992 - p. 31). This cross section is shown on seismic in figure 3.8, where a well developed sequence boundary is picked between the two well locations (15/13-1 is 6 km to the west of 15/13-2 but still penetrates the Upper Forties sequence Dornoch facies, not the Upper Balmoral). It will also be shown with seismic correlation below (figure 3.20) that the Lower Dornoch Sandstone of 14/30-1 (Knox and Holloway, 1992 - p.105) is not equivalent to the same named unit in well 14/25-1. The key to these points is that deposits which have been identified as Upper Forties lithostratigraphically, may have to be reinterpreted in light of depositional sequences if a chronostratigraphic equivalence is sought.

**Upper Forties sequence deposition**

The Upper Forties sequence rests on the Upper Balmoral sequence and is marked by an influx of *Apectodinium* spp. especially *A. augustum*, which appears almost exclusively within this sequence. The Upper Forties sequence marks the peak Paleocene regression, although in some locations the Middle Sele sequence shelf progrades slightly further into the basin. As discussed in figure 3.8, the relative sea level fall for this sequence is estimated at 150 m. The distribution of this fan has been mapped by Armstrong *et al.* (1987), Knox and Holloway (1992), and Stewart (1987). While precise picks and thicknesses may differ, general agreement can be reached on the map distribution of the Forties fan.

Figure 3.15 charts the distribution of mapping units within the Upper Forties sequence at the transition between pure bypass sedimentation in the
Fig. 3.15. Time structure map of the base Upper Forties sequence boundary with the map distribution of subunits and seismic expression of Map Unit A (UFA) and Map Unit B (UFB) within the sequence. The Upper Forties Fan deposition represents sandy midfan lobes, UFA is a combination of progradational (mainly to the north) and slumped (mainly in the south) sediments while UFB is purely progradational, onlapping UFA and onlapping the sequence boundary landward as it progrades basinward. UFA and UFB are separated by a mappable seismic discontinuity (see text for discussion). Seismic is courtesy of GECO-Prakla and Nopec and S.P.T. (Horizon Geophysical)
Time Structure (base Upper Forties sequence) C.I. = 50 msec.

- Upper Forties Map Unit A
- Upper Forties Map Unit B
- Main Upper Forties Fan deposition

- 0 km
- 60 km

Quad 14
Quad 15
Quad 16
Quad 20
Quad 21
Quad 22

Seism
UK
Everest Field
Montrose Field
Forties Field
Gannet Fields
Cod & Lomond Fields
basin and coastal deposition to the west. The Upper Forties Map Unit A (UFA) is mapped based on a strong seismic reflector within the Upper Forties sequence (figure 3.15). Using a depositional strike line across the Upper Forties sequence shelf, it is possible to demonstrate that this unit consists of prograding and chaotic internal reflections. The Upper Forties Map Unit B (UFB) is purely progradational and onlaps in a landward (west) direction. The UFB also onlaps UFA, demonstrated in seismic (figures 3.8 & 3.15) after UFA feeds directly through a deep incision in northwestern UK Quad 15. The chaotic reflectors of UFA are interpreted to represent slumped clinoform. These units, along with the main Upper Forties fan deposition document a transition from the lower lowstand bypass sedimentation to the stable progradation and onlap of the upper lowstand. UFA represents the attempts of an early lowstand delta to re-establish stable progradation, but the delta encounters depositional slopes too great for stability in some areas and slumping occurs. The slumped deposits and prograding remnants form a depositional slope more amenable for stable progradation of UFB. This transitional unit (UFA) illustrates the need for caution when applying the precise definitions of “slope fan” and “lowstand prograding” from published sequence stratigraphic models. It also provides another example of the diachronaiety of the top fan reflector that was recognized by Kolla and Perlmutter (1993).

**Middle Sele sequence and the aggradational phase**

The Upper Forties and Upper Balmoral sequences of the Upper Paleocene cycle can be described as the regressive phase in that they rapidly build out into the basin following the major transgression at the top of the Lower Paleocene cycle. The next three sequences (Middle Sele, Upper Sele, and Balder) represent aggradational and transgressive phases of the Upper
Paleocene second order cycle. These three sequences stack more vertically than the previous two with the Middle Sele sequence occupying the transition.

The Middle Sele sequence is positioned stratigraphically above a hiatal interval that often contains the FDO of A. augustum. The best biostratigraphic marker for this sequence is an acme occurrence of the acritarch, *Pterospermella*. The Middle Sele contains Hermod (Isaksen and Tonstad, 1989), Cromarty (Mudge and Copestake, 1992), and Flugga basinal sands, which were mapped by Knox and Holloway (1992) as well as Beauly coals in well 8/27a-1 (Chapters 2 & 4). The progradational shelf of the Middle Sele sequence, which normally falls within the upper part of the Dornoch Formation has been mapped from seismic (figure 3.16). Although technically more regressive than the Upper Forties shelf, the Middle Sele progradation is more aggradational and only locally progrades further into the basin. These localities are closely linked to tectonic elements with depocenters occurring to the north and south of Halibut Horst and a third to the south where subsidence-related faulting at the intersection of Moray Firth Basin and the Central Graben occurs.

The Upper Sele sequence is thin throughout the study area. The sequence is unresolvable with the present graphic correlation, however, a biostratigraphic signature of an influx of large leiospheres and an acme occurrence of *C. wardenense* distinguish this unit. The complications of a type log signature for this sequence are discussed above, therefore the sequence is noted here for its position within the aggradation/transgression phase of the Upper Paleocene second order cycle and the effect of that position on facies distribution.
Figure 3.16. Map distribution and seismic expression of a Middle Sele sequence sh Upper Forties sequence, showing the position of the Upper Forties shelf edge relati Forties serve as depocenters for the Middle Sele. Seismic data is courtesy of GECO
Shelf edge of Upper Forties sequence

- 50-100 msec. thick
- 100-150 msec. thick
- 150-200 msec. thick
- >200 msec. thick

Time structure (of top of U. Forties) contour interval = 50 msec.

Middle Sele sequence shelf edge delta. Time structure map is the top of the Forties shelf edge relative to the Middle Sele shelf. Lows in the top Upper Forties is courtesy of GECO-Prakla and Nopec.
**Balder sequence depositional system**

The Balder sequence is very complicated as third order sea level changes interfere with the increasing second order rise. The complexity of this sequence was demonstrated by Timbrell (1993) for the Beryl Embayment region to the north of our seismic coverage. In the basinal portion of the Central North Sea, this sequence is recognized within a tuffaceous claystone with low gamma ray values and a strong seismic reflection. This sequence seems to closely tie with the B2 subdivision of Knox and Holloway (1992).

Biostratigraphically, this sequence is marked by and acme of *D. oebisfeldensis* at its base and an acme of *Inaperturopollenites* spp. at its top. The radiolarian, *Coscinodiscus* sp. 1 of Bartenstein *et al.* (1962) also is found near the top of this sequence and an important hiatus is associated with this level. The difficulty in correlation occurs when the shelfal deposits of this sequence are tied to basinal observations.

The high amplitude seismic reflectors of the Beauly coal-bearing formation have a complex pattern of erosion that cannot be correlated regionally with any certainty. When viewed with strike sections (figures 3.17 and 3.18), thick deposits of this high amplitude seismic facies across Halibut Horst display distinct lobe geometries. In wells that penetrate these thicks (figure 3.18), multiple coal horizons are encountered within an overall sandy section. The discontinuous coal reflectors cap sediment lobes that onlap each other and backstep overall. Elliot (1986, p.124) describes a tide-dominated deltaic sequence saying, “The entire delta plain probably comprises a sheet-like complex of small-scale, erosive-based sequences which pass upward from point bar sand-silts into mangrove swamp facies, with localized clay plugs representing the infilled channel.” If the discontinuous coal reflectors are
Figure 3.17. Seismic expression and map distribution of some delta lobes and coals within the transgressive Balder sequence with the time structure map of the overlying Balder Hiatal Interval. Seismic horizons are identified by their overlying sequences: MSb = base Middle Sele sequence, USb = Upper Sele sequence, Bsb = Balder sequence, BHI = Balder Hiatal Interval, TFHI = Top Frigg Hiatal Interval. Seismic data courtesy of GECO-Prakla and Nopec. (see text for discussion).
Figure 3.18. Thick package of Balder sequence delta lobes in strike view, highlighting the discontinuous nature of coals capping the lobes. Also shown is a blow-up of the line illustrating an onlapping wedge of Lower Eocene (Frigg Undif.) sediments, infilling a sag of the Balder sequence over a Mesozoic Graben. The Balder package shows that multiple depositional shifts may be autocyclic or allocyclic (see text for discussion). Seismic data courtesy of GECO-Prakla and Nopec.
accepted as the remnants of the mangrove swamp facies, then Elliot could have been describing closely the well and seismic facies encountered in the Balder sequence shelf. An interpretation of a tide-dominated shelf seems reasonable for this setting as the present-day North Sea is known to have one of the stronger tidal regimes in the world due to its nearness to tidal resonance (Johnson and Baldwin, 1986). Figure 3.18 shows the map distribution of numerous delta lobes identified on seismic. Note especially the backstepped relationship of these deposits to the Upper Paleocene peak regressive shelf, highlighting the transgressive nature of this sequence, which was shown in figure 3.11.

*Lower Eocene (Frigg) cycles*

As well as displaying the backstepping within the Balder sequence, figure 3.11 highlighted a small magnitude, but important second order cycle in the Lower Eocene. Evidence for this cycle's shelf is problematic in most of the seismic coverage area due to similarities in facies distribution with the upper sequences of the Upper Paleocene cycle. Figure 3.18 displays an important sediment wedge onlapping the top of the Balder sequence in a location that has important connotations for the time represented by these deposits. This onlapping wedge is located over a Mesozoic graben. If the Balder sequence shelf is assumed to have been deposited at, or near baselevel, then the accommodation space created for this wedge could develop from subsidence related to differential compaction of sediment in the graben compared to lack of compaction over the horsts (Milton et al., 1990). With a compaction differential of 4 cm/ky between section over the graben compared to that over the horst, at least 1.5 My must pass before enough accommodation space is created for the 60(+) meters of sediment to fill.
Biostratigraphically, this wedge is not assigned an age in the Shell 14/24-2 well that penetrates it, however, the wedge sediments do overlie the PT 21 zone that has been correlated to the FDO of Coscinodiscus sp. 1 of Bartenstein et al. (1962) in nearby wells. The sediment overlying this wedge is designated PT 22/23, which covers the entire Lower and Middle Eocene (Den Hartog Jager et al., 1993). The overlying package has been traced to other wells with more detailed biostratigraphy and has been determined to be Middle Eocene in age. This makes the onlapping wedge Lower Eocene by process of elimination. When traced 5 kilometers to the west, this wedge has pinched out and the Upper-Middle Eocene lies almost directly on Upper Paleocene, similar to the pitchout relationship shown in figure 3.10.

The Lower Eocene cycle is poorly developed in the seismic coverage area for this study, but it has been better defined to the north in well 8/27a-1 and Frigg Field. At least three, and possibly four sequences have been recognized in this cycle and correlated to deposits in northwest Europe (Chapter 4). The evidence for this cycle in the seismic coverage area is subtle, but recognizable. In addition to examples shown in figures 3.18, and 3.10 through 3.12, the recognition of onlapping sediment fill of subsidence-related topography in the coals provides additional evidence for the Lower Eocene cycle. Figure 3.19 shows a seismic example of a sediment package filling one of these lows and the map distribution and thickness of the Lower Eocene shelf and bypass sediments. Key to recognizing this interval is the observation of a regional downlap surface above the coal reflectors. This surface is the top Frigg hiatal interval, which is normally associated with the FDO of Etonicysta ursulae. Although smaller in magnitude than the other second order cycles, the Lower
Figure 3.19. Time thickness map of the Lower Eocene (Frigg) regression shelf and some bypass units on a time structure map of the Balder hiatal interval. Displayed seismic illustrates the sag of Balder sequence coals and subsequent onlapping fill of Frigg-equivalent sediments that are then downlapped by the Upper-Middle Eocene regression (see text for discussion). Seismic data courtesy of GECO-Prakla and Nopec.
Eocene cycle fits the criteria set out for second order: it is comprised of multiple third order cycles and represents a reorganization of the depositional system.

**Upper-Middle Eocene and Lower Oligocene cycles**

The Upper-Middle Eocene cycle has as great a magnitude as the Upper Paleocene cycle, however, it is not nearly as well understood. Seismic data through the Middle Eocene is of poor quality due to disruption of reflectors by swarms of small faults related to dewatering of the sediment (Cartwright, 1993). Depositional models for this section are still evolving along with a refinement in the biostratigraphic framework. The stratigraphy presented by Newton and Flanagan (1993) with the biostratigraphic framework of Paleo Services closely resembles that observed in our study. For this reason, the lithologic units, Caran, Nauchlan, and Brioc have been adopted and appear in the summary framework below with biomarkers and hiatal intervals that we have found to be consistent.

The depositional systems of this cycle are poorly understood and published work has focused almost exclusively on depositional models for oil-bearing stringer sands in the slope environment (Newton and Flanagan, 1993; Harding et al., 1990). The shelfal system of this cycle, particularly the Nauchlan sequence, is very thick (over 300 meters) and progrades rapidly over the Lower Eocene and Upper Paleocene drowned shelf. Clinoforms on seismic indicate a paleobathymetry around 300m that was filled almost entirely with sand in the Witch Ground Graben (see figure 3.12). South of Halibut Horst, this sequence is siltier (figure 3.20) with much of the sand captured in transgressive deposits above the prograding package.

The top of the Upper Middle Eocene cycle is a major hiatal interval in the truest sense. The actual Eocene/Oligocene boundary is marked by the LAD of
Figure 3.20. Summary seismic line through Moray Firth Basin (see figure 3.1 for are: 1. Ekofisk, 2. Maureen, 3. Andrew, 4. Lower Balmoral, 5. Upper Balmoral, 6 Balder, 10. Frigg Undifferentiated (3-5 sequences), 11. Caran, 12. Nauchlan, 13. features on this line are discussed throughout the text. Lithology key: =chall 
=coal. Bold lines highlight second order cycle
(See figure 3.1 for location). Depositional sequences numbered to the left: 
Nauchlan, 13. Brioc, 14. Lower Lark 1, 15. Lower Lark 2. Labeled 
key:  - chalk,  - basinal sands,  - mudstone,  - silt, 
second order cycles. Seismic data is courtesy of GECO-Prakla and Nopec.
*Areosphaeridium diktyoplokos* (Vinken, 1988). The boundary is a major marine hiatus in the basin (Harding *et al.*, 1990), and on the shelf this marker ranges within transgressive sands that often contain fossils of the entire Upper Eocene. The result is the largest graphic correlation terrace recorded in the North Sea (figure 3.12). Examination of this age in outcrops of northwest Europe reveal a similar phenomena as the transgressive Bassevelde sand of Belgium (Vandenberghe *et al.*, 1992) is reported to contain nannofossils of NP 18-21 zones (figure 3.21). The upper boundary of the Upper-Middle Eocene cycle is thought to represent a slow transgression with decreased sediment supply before regression reoccurs in the Lower Oligocene.

The Lower Oligocene marks a shift in sediment delivery to the North Sea from Britain to Norway (Michelsen *et al.*, in press; Galloway *et al.*, 1993). Biostratigraphic control for this section is poor since few well reports log samples within these sediments. In the few wells that do contain biostratigraphy, this cycle appears to be bracketed by *A. diktyoplokos* at its base and *A. arcuatum* at its top. In shelfal wells, two depositional sequences can be distinguished, which expand into silty thicks in the basin. Figure 3.20 shows many of the features described within the nested stratigraphic cycles above and serves as a good overview.

**Discussion and Regional Correlation**

The nesting of stratigraphic cycles in the Paleogene North Sea is believed to represent an interference of eustatic and tectonic signals. Theoretically, stratigraphic signatures of eustasy and tectonics are recognizable with low frequency cycles representing tectonic mechanisms and high frequency cycles representing eustasy (Vail *et al.*, 1991). Cloetingh (1988) has suggested an intra-plate stress tectonic mechanism for “third order”
Fig. 3.21 (A & B). - Chronostratigraphic chart for the Paleogene of Northwest Europe.  

1. Revised time scale from Cande & Kent (1992), with nanofossil correlations from Aubry et al. (1988) - part of Hardenbol et al. (in prep.).  


$\text{New (O & SS)}$ = position of a sequence boundary from outcrop and subsurface data not picked in Haq et al. (1988).  

$\text{New (O)}$ = position of a sequence boundary from outcrop data not picked in Haq et al. (1988).  

Correlation of the frameworks from Den Hartog Jager et al. (1993), and Armentrout et al. (1993) are based on biostratigraphic tie points. The Haq et al. (1988) eustatic curve is modified based on a correlation of nanofossil zone differences between Haq et al. (1988) and Aubry et al. (1988)

**Lithology and Facies key**

- Hemipelagic Mud/Marine H hiatus
- Lowstand Prograding Tuff
- Dominantly-Silt Turbidites
- Transgressive Surface sandshale
- Dominantly-Sand Turbidites
- Transgressive Shoreface/Estuary Sands
- Graphic Correlation Data Terrace Erosion or Missing Section
- Highstand Silt/Sand Sequence Boundary (SB)
- Incisive SB Allochthonous Chalk Debris Pelagic Chalk
relative sea level changes that would make global correlation of cycles at this frequency difficult. At present, the most comprehensive published eustatic chart is that of Haq et al. (1988). The sequence stratigraphic framework developed in this study is compared with the Haq et al. (1988) chart (figure 3.21). The stratigraphic framework presented here has been built from the subsurface sequence stratigraphy described above, integrated with published rock and biostratigraphic information from northwest Europe (Chapter 4). Stratigraphic frameworks of Shell (Den Hartog Jager et al., 1993) and Mobil (Armentrout et al., 1993) were correlated based on biostratigraphic tie points and an observation of similar positioning of events in each framework. A nearly one-to-one correlation of events observed in this study with those noted by Den Hartog Jager et al. (1993) is apparent.

The test of a eustatic signal comes by comparing events documented in this study to those predicted by the Haq et al. (1988) curve. Based on biostratigraphic correlations, this comparison demonstrates that a eustatic signal can be identified in northwest Europe, but additional cycles are required to fully describe the sections. The eustatic curve has been modified here by matching the nannofossil zones of Haq et al. (1988) to those of Aubry et al. (1988), correlated to the revised magneto-chronostratigraphy of Cande and Kent (1992). Nannofossil zones are correlated to planktonic foraminifera zones (J. Hardenbol & W.A. Berggren, pers. comm. 1994), which provide the true link of biostratigraphy to magnetostratigraphy, therefore these correlations should be regarded as tentative until a revised correlation of nannofossils to foraminifera is published for the new time scale. Integration of sequences observed in northwest Europe with those observed in the North Sea using a consistent biostratigraphy and graphic correlation suggests that all events on
the Haq curve appear in northwest Europe with 7 previously uncharted sequences being necessary to accurately describe the sections at this time (figure 3.21).

It is not surprising that a good correlation with the Exxon curve should be achieved in this section as northwest Europe was one of the key regions used in the construction of this part of the chart (Haq et al., 1988). The observation of additional cycles follows with an improvement of the database and resolution, similar to an improvement in resolution from the charts of Vail et al. (1977) to that of Haq et al. (1988). The documentation of second order cycles in northwest Europe, however, indicates stratigraphic complications resulting from differential tectonic uplift as predicted by Vail et al. (1977, 1991).

Second order cycles can correlate closely throughout northwest Europe, but they can also occur $180^\circ$ out of phase, depending on local and regional tectonic regimes. A close tie is achieved for the Lower Paleocene cycle throughout northwest Europe as indicated from major unconformities in western basins (Paris, Belgium and London-Hampshire) below the Thanetian transgression (figure 3.21). This is also a change in sedimentation from limestone to clastics associated with an unconformity in Denmark (Heilmann-Clausen et al., 1985) and peak uplift in the northern Britain (Musset et al., 1988). The Lower Oligocene cycle is completely out of phase, though, comparing Denmark and the North Sea with western European basins. Uplift of Norway and the Skagerak-Kattegat Platform (Michelsen et al., in press; Japsen, 1993) caused regression in the North Sea at the same time the Rupelian transgression was occurring to the west. High frequency events are correlative across this time interval, but the expression of those cycles varies greatly from one sub-basin to another.
Additional complications arise when attempting to distinguish different magnitudes of third order cycles due to interference from second order cycles. This case is best shown from two examples, one in the Uppermost Paleocene and the other from the Lower to Middle Eocene. As discussed above, a 150 m relative sea level fall is demonstrated from seismic data at the base of the Upper Forties sequence in the North Sea. Based on biostratigraphic correlations, the same sequence boundary falls at the base of the Lambeth Group (Ellison, 1993; Jolley, 1993), with little evidence for 150 m incisions (figure 3.21). Conversely, in western onshore basins, a major subaerial unconformity is recognized at the Lower-Middle Eocene boundary (Aubry et al., 1986) with major incisions of the Belgium coast (DeBaptist, 1989) at the same time a major marine hiatus is recorded in the Central North Sea (figure 21). These differences represent the enhancement or subduing of high frequency cycles by their position on a low frequency cycle (Vail et al., 1991).

Chapter Conclusions

Recognition of nested stratigraphic cycles has important implications in basin stratigraphic analysis. Integration of the techniques of sequence stratigraphy and graphic correlation provides the tools and models that aid in the resolution and correlation of sedimentary deposits in widely scattered locations with different depositional environments. By building the best possible chronostratigraphic framework and understanding the limits of its resolution, stratigraphic events are correlated with some degree of confidence. Our study has shown that a high frequency ("third order") signal can be documented and correlated through many different depositional environments with a consistent biostratigraphy. Low frequency events are not the most reliable chronostratigraphic units for correlation outside a given tectonic provenance.
due to local complications and interference by the high frequency signal. The high frequency sea level signal documented by this study appears to correlate well with that of Haq et al. (1988) and Den Hartog Jager et al. (1993).

The depositional systems of the North Sea are controlled by second and third order sea level cycles as well as sediment source and supply, depositional profile, and differential compaction subsidence. The second order cycles represent a reorganization of the depositional system and are comprised of multiple third order cycles. Third order cycles control the distribution of lithofacies and individual reservoir and seal rocks in the basin. Their character is a function of position within a second order cycle. They are correlated within a framework of graphic correlation hletal intervals. The depositional profile controls the distribution and expression of depositional systems tracts and the paleogeographic model. Differential compaction subsidence creates space for sediments, and suggests relative time represented by deposition and hiatus.
Chapter 4

Graphic Correlation and Sequence Stratigraphy in NW Europe

Chapter Summary

A sequence stratigraphic analysis of well log, seismic, and biostratigraphic data has documented a pattern of cyclic sedimentation for the Paleogene of the Central North Sea. Previously published research has also documented cyclic sedimentation related to sea level changes. Integrating Central North Sea subsurface sections with Paleogene outcrop from NW Europe, using sequence stratigraphic first principals and the graphic correlation method, has produced a chronostratigraphic framework for the Paleogene of NW Europe.

Northwestern Europe basins (London-Hampshire, Paris, and Belgian) have shallow marine to nonmarine environments, revealing basinward and landward facies shifts indicating sea level changes. The problem correlating NW Europe with North Sea deposits has been addressed by correlating a biostratigraphy to the deep water deposits outcropping in Denmark. Once a biostratigraphy joining the subsurface and outcrops is built, key bounding surfaces are correlated between basins. We find that: (1) sedimentation in the deep basin occurs as depositional pulses, separated by time-correlative biostratigraphic data terraces (hiatal intervals), which correspond to persistent seismic reflectors; (2) not all sequence boundaries are resolvable by graphic correlation, but the method brackets packages defined by seismic, log interpretation and biostratigraphy; and (3) correlation with outcrops reveals the true significance of the hiatal intervals.
Introduction

Hydrocarbon exploration in the Central North Sea has convoluted a standard stratigraphic nomenclature as consultants and exploration companies developed informal lithostratigraphic schemes with proprietary biostratigraphic information. An attempt at a standard lithostratigraphy was first published by Deegan and Scull (1977). However, lithostratigraphy has been criticized for its inherent diachronality (Bertram and Milton, 1988). Biostratigraphy has been used in recent lithostratigraphic work (Mudge and Copestake, 1992; Knox and Cordey, 1992) to trace different units, but these units remain diachronous, to varying degrees, because of the nature of lithostratigraphy (Bertram and Milton, 1988; Stein et al., in press).

Fossil zonations have been widely used in the North Sea (e.g. Stewart, 1987; Powell, 1988; Gradstein et al., 1992). A detailed zonation scheme developed by Simon-Robertson Limited has been used by some authors (e.g. Timbrell, 1993) for correlation, however, this and many other zonation schemes (e.g. Den Hartog Jager et al., 1993) remain largely unpublished and difficult to tie to the published frameworks. The increased emphasis recently placed on individual biomarkers (e.g. Mudge and Bujak, in press; Morton et al., 1993) may have problems with reaching consensus on taxonomic designations between workers, using unpublished or rare species, and identifying environmentally depressed or reworked tops (Armentrout, 1991). The graphic correlation/composite standard method of biostratigraphy, integrated with geological and geophysical bounding surfaces, builds a consistent chronostratigraphic framework that mitigates these problems.

Superposition relationships, shifts in depositional environment, and major sedimentologic changes are critical when determining the sea level
history of a particular location within the basin. However, correlating important surfaces with biostratigraphy is needed for temporal control that places local observations into a basinwide stratigraphic framework. A consistent biostratigraphy makes it possible to build a sequence stratigraphic framework that explains known deposits and suggests undiscovered ones. This paper discusses the role of the graphic correlation/composite standard biostratigraphic method in the construction of a sequences stratigraphic framework for the Paleogene Central North Sea and connecting Northwest European basins.

Previous Studies

The stratigraphy of the lower Paleogene section of the Central North Sea has evolved with the development of higher quality seismic data and numerous well penetrations since the first basinal studies of Parker (1975) and lithostratigraphic nomenclature of Deegan and Scull (1977). Major field discoveries in the late 60's and early 70's focused mainly on structural traps. As the basin entered a more mature phase of development, emphasis shifted towards unraveling the stratigraphy represented in those fields. Rochow (1981) published the first seismic stratigraphic study of the North Sea "Palaeogene", relating seismic units to the lithostratigraphic division of Deegan and Scull (1977). Stewart (1987) followed with a 10-sequence division of the section, incorporating seismic and well data, tied to a biostratigraphic framework. Stewart's (1987) framework was related to tectonics by Milton et al. (1990), exploring the idea of nested high and low frequency sea level change cycles.

Recently, a series of papers were published in a volume edited by Parker (1993) that cover a range of time scales and stratigraphic tools. Galloway et al. (1993) propose a tectono-stratigraphic framework for the entire Cenozoic and is
the lowest resolution but most regional of these studies. Timbrell (1993) focuses
on the Lower Eocene only and the stratigraphic complexity of the Balder and
Frigg sections, while O'Connor and Walker (1993) unravel the stratigraphy of
the Lista/Sele Formation boundary within a sequence stratigraphic framework.
Morton et al., (1993) use heavy mineral analysis along with biomarker
stratigraphy to subdivide the section and Vining et al., (1993) emphasize
palynofacies with respect to sea level changes. Den Hartog Jager et al., (1993)
and Armentrout et al. (1993) present regional frameworks on a scale similar to
our study, emphasizing the integration of seismic and well data. Other regional
studies on the Paleogene focus more on seismic geometries related to tectonics
(Milton and Jones, in press) and biostratigraphic markers related to well log
picks (Mudge and Bujak, in press).

Material and Methodology

The correlations presented here come from an integration of the graphic
correlation method of biostratigraphy (Shaw, 1964; Miller, 1977) with sequence
stratigraphic principals (Vail et al., 1977; Posamentier et al., 1988; Vail et al.,
1991). A 7400 km seismic grid (figure 4.1) covers the study area and
approximately 100 well logs tied by synthetic seismograms provide geologic
information to supplement seismic facies analysis. Of those wells, 40 have
detailed biostratigraphic reports and are part of the 150 wells with detailed
biostratigraphy that were compiled to build a North Sea composite standard
from Amoco's global composite standard (Stein et al., in press).

The composite standard is a chronostatigraphic range chart of all fossil
appearances that occur in a series of stratigraphically overlapping reference
sections, thus creating an ideal composite section for comparison with
individual sections being studied. Figure 4.2 is a portion of the North Sea
Fig. 4.1 - Map of northwestern Europe with the location of North Sea wells and seismic lines in addition to key outcrop and borehole sections. Labeled Pre-Tertiary structural elements are: E.S.P.=East Shetland Platform, W.G.G.=Witch Ground Graben, S.V.G.=South Viking Graben, & F.M.H.=Forties-Montrose High.
<table>
<thead>
<tr>
<th>Published Markers &amp; a G.C. Terrace</th>
<th>CSU</th>
<th>Relative Chronological Position of Last Appearance Datums and Acme Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>-760</td>
<td></td>
<td><em>Gillozomma magnus</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ceratolithus sp. Type 6 RRI</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Acme <em>Deltamia beechei</em>, <em>Promea fragilis</em>, <em>Wetzelia aster</em></td>
</tr>
<tr>
<td>-750</td>
<td></td>
<td><em>Podastrea palaionigra</em></td>
</tr>
<tr>
<td>-740</td>
<td></td>
<td>Subtilisphaera sp. 1 RRI</td>
</tr>
<tr>
<td>-730</td>
<td></td>
<td><em>Leiosphaera large, Acme Ceratopsis wardianensis, Ceratopsis speciosa</em></td>
</tr>
<tr>
<td>Bioevent (M6)</td>
<td></td>
<td><em>Mitrapectenitella</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Rhabdosphaera gracilis</em></td>
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<tr>
<td></td>
<td></td>
<td><em>Pseudosphaera micropores</em></td>
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<tr>
<td></td>
<td></td>
<td>*Cosmosphaera sp. 15 Paleo Services, Diatom sp. 34 Paleo Services</td>
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<tr>
<td></td>
<td></td>
<td><em>Cosmosphaera</em> <em>beaumonti</em>, <em>Gigantea</em>, <em>Cosmosphaera sp. 1 Goosetel</em></td>
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<tr>
<td></td>
<td></td>
<td><em>Rhabdosphaera asteroaestiva</em></td>
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<td></td>
<td></td>
<td><em>Apectodinium hypericum</em></td>
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<td></td>
<td></td>
<td><em>Promea fragilis</em>, <em>Simpanspermites</em></td>
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<td></td>
<td></td>
<td><em>Apectodinium pinnatum</em></td>
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<td></td>
<td></td>
<td><em>Apectodinium fragilis</em></td>
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<td></td>
<td></td>
<td><em>Pseudoalterea sp.</em></td>
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<td></td>
<td></td>
<td>*Cosmosphaera sp. 8 RRI</td>
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<td></td>
<td></td>
<td><em>Ceratopsia acetosa gracilis</em>, <em>Acme Pterospermites</em></td>
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<td></td>
<td></td>
<td><em>Hinnitulites</em> <em>pathyanostratus</em></td>
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<td></td>
<td></td>
<td><em>Cicatrosarctites</em> <em>Group C RRI</em></td>
</tr>
<tr>
<td>-710</td>
<td></td>
<td><em>Acme Deltocone sp.</em></td>
</tr>
<tr>
<td>Sele Hiatus (Top Forties)</td>
<td></td>
<td><em>Cicatrosarctites</em> <em>Group A RRI</em></td>
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<tr>
<td>Bioevent (P3)</td>
<td></td>
<td><em>Apectodinium augustum</em>, <em>Spinodiium densispinatum</em></td>
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<td></td>
<td></td>
<td><em>Acme Apectodinium</em></td>
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<td></td>
<td></td>
<td><em>Globorotalia chapmani</em></td>
</tr>
<tr>
<td>-690</td>
<td></td>
<td><em>Rhizodinium magniflorum</em>, <em>Acme Leuonecyra</em> sp.</td>
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<td></td>
<td></td>
<td><em>Pseudopunctation sp.</em></td>
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<td></td>
<td></td>
<td><em>Ceratolithus aciculatus</em></td>
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<td></td>
<td></td>
<td><em>Gephyrocapsa reticulata</em></td>
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<tr>
<td></td>
<td></td>
<td><em>Acme Ceratolithus vegetis</em></td>
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<td></td>
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<td><em>Homorotalia palaicum</em></td>
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<tr>
<td>Bioevent (M5)</td>
<td></td>
<td><em>Rhizammina/Bathyphorum</em> (Reappearance)</td>
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<tr>
<td>Bioevent (M4)</td>
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<td><em>Schlopedolithus aciculatus</em></td>
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<tr>
<td>Bioevent (P2)</td>
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<td><em>Rhizodinium magniflorum</em></td>
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<td></td>
<td></td>
<td><em>Gephyrocapsa</em> <em>reticulata</em></td>
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<td><em>Aulacospira margarita</em>, <em>Aulacosphera affinis</em></td>
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<td></td>
<td></td>
<td><em>Trachyceratites subtruncatus</em></td>
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<td></td>
<td></td>
<td><em>Trachyceratites subvaceolatus</em></td>
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<td></td>
<td></td>
<td><em>Aulacophragmium</em> <em>sp. 1 Gielisland &amp; Berggren, 1997</em></td>
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<td></td>
<td></td>
<td><em>Aulacospira affinis</em></td>
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<tr>
<td>Bioevent (P2)</td>
<td></td>
<td><em>Cosmosphaera</em> <em>sp. 17 RRI</em></td>
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<tr>
<td>Bioevent (P2)</td>
<td></td>
<td><em>Asterias of subspencasensis anser</em> RRI</td>
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<tr>
<td></td>
<td></td>
<td><em>Spiniferites limicola</em></td>
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<td><em>Spiniferites</em> <em>mombaloides</em></td>
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<td><em>Leptodinium</em> <em>subolatum</em></td>
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<td><em>Ceratopsis stria</em>, <em>Pseudoalterea fusca</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Tognicapitella</em> <em>genita</em>, <em>Cosminthera bonelli</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Rhizammina</em> <em>costata</em></td>
</tr>
</tbody>
</table>

*Figure 4.2. Portion of the composite standard used in this study for the Upper Paleocene and lowermost Eocene ages.*
composite standard in the Upper Paleocene/Lower Eocene showing the relationship between composite standard units (CSU) and the superposition of various fauna. By creating X-Y crossplots of a well or outcrop section against the composite standard, the biostratigrapher demonstrates graphically where stratigraphic gaps appear relative to the most complete section possible for the basin (Shaw, 1964; Miller, 1977). Stein et al.. (in press) describe in detail the necessary steps to build a composite standard for a specific basin. This process alters the global standard observed from other basins to account for taxa not globally recognized and for extended or shortened phylogenic ranges of taxa already in the global standard. Many well sections in a basin must be studied before a mature composite standard is produced. This insures that depocenters of many ages are incorporated into the standard and lessens the chance of sampling bias. CSU's are nonlinear values that represent the chronological position of a fossil relative to others in the composite standard. Calibration of CSU's to various chrono-biostratigraphic charts (e.g. Haq et al., 1988; Harland et al., 1990) derives an absolute time value for the units. Regardless of the absolute time calibration, CSU's provide an indication of relative time and, therefore, relative rock accumulation (sedimentation) rates (Shaw, 1964).

A simplified example of the graphic correlation procedure is illustrated in figure 4.3. Graphic correlation interpretations start by plotting reported fossil tops by depth occurrence (vertical axis) against time in CSU's (horizontal axis). The scatter of points is then connected by an interpreted line of correlation (LOC), drawn with straight lines to honor the highest number of data points. The LOC approximates relative sedimentation rates (not accounting for differential compaction) as resolvable by the fossils. Interpretation of the biostratigraphy identifies at least two horizontal data terraces, representing missing or
Fig. 4.3. Diagramatic example of the graphic correlation procedure and interpretation. Lithology key: 

- sand, 
- silt, 
- shale.

Composite Standard Units have a linear scale for this example only (see text for further explanation).
condensed section, separating sloping line segments characteristic of higher depositional rates (Sediment Pulse). Also plotted are fossil tops occurring out of normal succession due to local conditions. These tops distort chronostratigraphic frameworks that are based only on key markers (Stein et al., in press). For example, fossil G plots above and to the left of the LOC, indicating an extended range or reworked occurrence. This observation has important implications for correlation of stratigraphic breaks. Fossil G is normally found above F and below H, according to the chronostratigraphic range chart. In the example well, fossils F and H define a stratigraphic break that would normally contain the top of fossil G. If fossil G is regionally used as the key marker for this break, a significant amount of section falls within an incorrect chronostratigraphic unit (figure 4.3).

The geological meaning of a graphic correlation terrace is dependent on the depositional setting, data sampling and resolution of the biostratigraphic data. Graphic correlation terraces in a shallow marine setting have been shown to correspond to major unconformities or faults in lithofied sections (Shaw, 1964; Miller, 1977). If the terrace is regionally extensive and time correlative in an unfaulted passive margin setting and separates younger from older sediments, it can, by definition, be identified as a sequence boundary or composite sequence boundary (Mitchum and Van Wagoner, 1991). In a bathyal environment such as that illustrated in figure 4.3, the time represented by sandy “fan” deposits is half that contained within the intervening data terraces. This relationship is consistent with published sequence stratigraphic models that predict decreased sedimentation rates in the submarine fan setting during periods of relative rise, which occurs during lowstand prograding, transgressive, and highstand systems tracts (Vail, 1987; Posamentier and Vail, 1988;
Posamentier et al., 1991). In the Central North Sea, graphic correlation data terraces often occur within a single sample interval and may equate with over a million years of geologic time when calibrated to a chrono-biostratigraphic chart (e.g. Haq et al., 1988). Data terraces may also occur at sand-on-sand contacts in the submarine fan setting. These observations suggest that data terraces contain significant hiatuses, rather than simple condensed section.

**Hiatal Intervals**

Hiatus formation is a complex subject with many potential hiatus-forming mechanisms being only indirectly related to changing sea level. For example, in continental slope and rise environments, hiatuses may be formed by slumping (Aubry, 1991), non-deposition, erosion, or dissolution (Pomerol, 1989). The indirect tie to sea level links sediment supply in these environments to changes in shelfal accommodation space for sediments. Falling sea level increases shelfal bypass of sediments, causing a pulse of sediment to be delivered to the slope (Posamentier et al., 1991). Rising sea level ponds sediment landward, starving the slope of sediments and increasing the potential for submarine erosion due to bottom current activity or dissolution. Key surfaces from different locations are correlated as resulting from a single event, if the hiatuses associated with each surface are shown to overlap in time (Aubry, 1991). Inherent uncertainties in the raw data must be considered when interpreting condensed sections or hiatuses. Biostratigraphic datums are most often picked from cutting samples taken at 30 foot/10 meter intervals, but any given well may have larger data gaps due to drilling problems, barren samples, or lack of economic interest. These sample gaps may cause misplacement or apparent lengthening of a terrace (Shaw, 1964).
Figure 4.4 expands upon the major data terrace between 5600 ft and 5700 ft of figure 4.3 where different sedimentation rate histories may be interpreted from the same data. Using the condensed section approach of Loutit et al. (1988), continuous sedimentation at a greatly reduced rate occurs through the interval containing fossils F and H. In this interpretation, no hiatus exists ("correlative conformity" of Mitchum et al., 1977), only greatly reduced continuous sedimentation represented by multiple fossil tops and a curvilinear sedimentation rate curve. Nondeposition is mentioned by Loutit et al., (1988), however, the possibility of a complex sedimentation history of deposition and erosion for slope settings (e.g. Aubry, 1991) is ignored.

A cored borehole, sampled in detail, will identify tops or last appearance datums (LAD's) at a higher resolution than normal cutting samples (figure 4.4). The "actual" sedimentation rate curve is a subjective line based on LAD's in the well as they would appear in a core and the relative sedimentation rate of turbidite sands versus hemipelagic drape (Kolla and Macurda, 1988). The possible complexity around the tops of fossils F and H illustrate that neither the graphic correlation line nor the condensed section line accurately describe the depositional history. The graphic correlation line better approximates the episodic nature of these deposits, but is limited by data resolution.

Geologic time is represented in the rock record by either deposition or omission surfaces like unconformities or fault planes (Shaw, 1964). Graphic correlation data terraces represent some omission or condensation of section, as identified by the biostratigraphic resolution. We propose the use of "hiatal interval" as a generic term for section where data resolution does not permit accurate partitioning of time represented by rocks and surfaces. Graphic correlation may identify a data terrace where sampling resolution is insufficient
Fig. 4.4. - Diagramatic illustration of possible stratigraphic complexities (Actual line) around a hialal interval with an interpretation of biostratigraphy from cuttings using graphic correlation and a condensed section approach. Data points are plotted at the base of each sample interval as they appear in standard well reports, the "Actual" line is based on the exact position of each marker in a cored section (see text for discussion).
to accurately determine the geologic time duration represented by either the deposits or the omission surfaces within a package. A hiatal interval is different from a condensed section. Hiatal intervals infer the complex sedimentation and erosion history that may occur in hemipelagic sediments (Aubry, 1991), but requires resolution beyond that available from the sampling at hand to document. Hiatal intervals of this study represent significant time intervals and are correlative markers bracketing sequences. Condensed sections may occur in multiple positions within a sequence (e.g. top basin floor fan, top slope fan, or maximum flooding surface - see Vail and Womardt, 1990), and may not represent a significant time interval. Many sections interpreted as condensed may, in fact, be hiatal intervals and require further study to decipher their complexity.

Mitchum and Van Wagoner (1991) identify high frequency sequence boundaries that result from the interference of high and low frequency sea level changes. While these events may be recognized in the shallow marine depocenters as basinward shifts of facies, their expression in the deep marine setting is difficult to distinguish from normal autocyclic processes such as fan lobe avulsion. Long term rises in sea level partition more sediment in shelfal than basinal areas (Duval et al., 1992). Superimposed on long term rises are short term falls that can be recognized as facies shifts in the shallow section, but may or may not have expression in deep basin deposits. Correlation of basinal hiatal intervals with time-equivalent outcrop in Northwest Europe reveals that multiple sea level changes may be identified in outcrop within the time span of a hiatal interval in the deep basin. The hiatal interval between 5600 ft and 5700 ft (figure 4.4) is an idealized example of this high frequency signal resolved in a basinal setting. During a long term rise, sedimentation rates in the basin will
decrease, potentially allowing submarine erosional processes to remove sediment that represents a long period of geologic time. Short term sea level falls, however, may result in minor pulses of sediment into the basin which are unresolvable with normal 30 ft cutting samples (e.g. between top F and top H). Without outcrop or core data that enables dense sampling of condensed sections, hialtal interval correlation is the most accurate means of separating sediment pulses in the deep marine setting, and identifying chronostratigraphic units.

**Application of the Graphic Correlation Method**

The depositional sequences presented here borrow lithostratigraphic names from the lithostratigraphic frameworks of Deegan and Scull (1977), Isaksen and Tonstad (1989), Mudge and Copestake (1992), and the Paleo-Services/Chevron framework of the Mid-Upper Eocene (Newton and Flanagan, 1993). Figure 4.5 illustrates the correlation of depositional sequences used in the Paleocene to Lower Eocene section to lithostratigraphic units from type wells of Mudge and Copestake's (1992) and Isaksen and Tonstad's (1987) frameworks. Also displayed here is a correlation to depositional sequences published by Stewart (1987), using his well sections and maps as tie points. The diachronaiety of Stewart's (1987) sequences illustrates the need for a framework, founded on biostratigraphy, then tied to wells and seismic.

Sequences do not always correlate with their lithostratigraphic equivalents. Sequences are identified by their biostratigraphy and position on a graphic correlation LOC, related to surfaces on seismic and logs. As such, they are chronostratigraphic units and the same sequence may contain more than one lithostratigraphic unit. Describing a type log signature for any sequence is problematic as illustrated by the "Upper Sele" sequence. This sequence
Figure 4.5. Correlation of depositional sequences, key biostratigraphic markers, and hiaital intervals with namesake lithostratigraphic units from recently published frameworks. Abbreviations for lithostratigraphic units: E=Ekofisk Fm., M=Maureen Fm., A=Andrew mbr., G=Glamis mbr., Balm=Balmoral mbr., L=Lista Fm, S=Sele Fm., F=Forties mbr., D=Dornoch mbr., B=Beauly Fm., Fa=Farvel Fm., Fg=Frigg Fm., Hr=Hermod Fm., Hm=Heimdal Fm. Also shown are Stewart's (1987) sequences: S = type section for the sequence (see text for discussion).
<table>
<thead>
<tr>
<th>DEPOSitional SEQUENCE</th>
<th>NP (Fm)</th>
<th>Key Biostratigraphic Marker</th>
<th>Lithostratigraphic Units</th>
<th>Stewart ('97)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>1</td>
<td>E. unio&lt;sup&gt;a&lt;/sup&gt;</td>
<td>101:1-1</td>
<td>101:1A</td>
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<td></td>
<td>14</td>
<td>M.E. unio&lt;sup&gt;a&lt;/sup&gt; - H. balteum&lt;sup&gt;a&lt;/sup&gt;</td>
<td>21:13-1</td>
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<tr>
<td>Upper Frigg</td>
<td>13</td>
<td>C. enhardii&lt;sup&gt;a&lt;/sup&gt;</td>
<td>21:10-1</td>
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<td></td>
<td>11</td>
<td>H. longissima&lt;sup&gt;a&lt;/sup&gt;</td>
<td>21:9-1</td>
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<td></td>
<td>12</td>
<td>H. gemma&lt;sup&gt;a&lt;/sup&gt;</td>
<td>19:1A</td>
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<td>11</td>
<td>H. cornuta&lt;sup&gt;a&lt;/sup&gt;</td>
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<td></td>
<td>10</td>
<td>D. kondylo&lt;sup&gt;a&lt;/sup&gt;</td>
<td>10:1-1</td>
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<td></td>
<td>9</td>
<td>D. angulata&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>D. angulata&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>D. angulata&lt;sup&gt;a&lt;/sup&gt;</td>
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typically has acme occurrences of the dinocysts, *Cerodinium wardenense* (Williams & Downie, 1966) at its base and *Deflandrea oebisfeldensis* (Alberti, 1959) at its top. In type wells for each lithostratigraphic framework, these markers may be found together or separated, in the Balder Formation (tuffaceous claystone), Sele Formation (dark grey clay), Hermod Formation (deep water sandstone), or in their shelfal equivalent Beauly Formation.

A 30 m 'error bar' between the reported fossil depth occurrence and the well log pick was used by Armentrout et al., (1993), to account for operator consistency and seismic resolution. Using this margin of error allows great freedom in making a sequence pick fit the data. Generally, we tried to achieve precise agreement between at least two of the three disciplines used in this study (log interpretation, paleontology, and seismic interpretation). The error bar mentioned by Armentrout et al., (1993) is one way to reconcile a mistle of biostratigraphy with well log and seismic interpretation. When sequences are below seismic resolution or occur within a seismically chaotic zone, well log interpretation and fossils are the only tools that allow correlation with any confidence.

Sequences are picked on individual well logs based on an interpretation of the relative sea level signal for each particular location, correlated with biostratigraphy. For example, in deep water settings, the base of the Upper Sele sequence occurs at a high gamma marker on electric logs near the reported acme occurrence of *C. wardenense* from cuttings. The sequence boundary is interpreted to be combined with the underlying maximum flooding surface. The sequence boundary marks renewed basinal deposition due to a fall in relative sea level and shelfal bypass, depositing sediment containing abundant *C. wardenense*, capped by hemipelagic drape containing abundant *D.*
*oebisfeldensis*. In shelfal settings, the sequence boundary occurs at the base of a thick coal, an incised valley deposit, or at the base of a transgressive sandstone. These deposits may overlie a high gamma shaly section interpreted to represent periods where sediment is ponded in a coastal system to the west. The coal represents the remains of a marsh and a base level zero datum (Milton *et al.*, 1990). Thick, rooted coals are indicators of transgression (Cross, 1988), therefore, their bases are likely exposure surfaces. Not all coals overlie sequence boundaries, however, as the Balder sequence (Beauly Formation) contains many coals that are discontinuous and simply reflect delta lobe abandonment within an overall transgressive package.

**Deep water environment example of graphic correlation**

The composite standard for the Central North Sea has been largely built and utilized in the deep marine environment where correlation of turbidite packages relies on good biostratigraphy. A sequence stratigraphic interpretation involves a series of steps that begins with interpretation of the biostratigraphic data, followed by picking sequences on the well logs that are tied to seismic with synthetic seismograms, and finally correlated with seismic between well control points. Figure 4.6 is a typical basinal well for the North Sea Paleogene with gamma ray curve, lithology and the biostratigraphic top or acme datums from a well report. Plotted to the right of the well are biostratigraphic datums at their reported depth and relative age within the composite standard for the Central North Sea (in non-linear composite standard units). A LOC is interpreted with the scatter of points. Since the composite standard for the North Sea was built using North Sea wells, individual wells are plotted against the standard in later iterations minus the well itself, to avoid a circular interpretation.
Fig. 4.6 - Graphic correlation and sequence stratigraphic interpretation of UK well 1628-1. Data points are first downhole and acme occurrences of various taxa, distinguished by symbol. Paleobathymetry is given as bathyal and open marine for the entire section (paleobathymetry estimates courtesy S.P.T. - Robertson Research). Lithology symbols: chalk, isolated limestones, shale, silt, sand, tuff.
Where graphic correlation identifies a hiatal interval, it is possible to place a sequence boundary on well logs at, or near the interval, using the 30 m 'error bar'. Sequence boundary picks come directly from well log interpretation of key surfaces, aided by integration of paleobathymetric and biochronologic information. Often, high gamma shales are used to pick genetic sequences (Galloway, 1989; Stewart, 1987). These high gamma intervals, which are interpreted to represent very slow sedimentation, divide the section stratigraphically into sediment pulses. In a basinal well, sequence boundaries are picked at the base of each sediment pulse. In the deep marine environment, this approach is possible because highstand and transgressive deposits are not well-represented and result in merged sequence boundaries and maximum flooding surfaces (Vail, 1987). However, in a sand-rich turbidite environment such as the Paleogene Central North Sea, submarine scouring may produce a sequence boundary in wells that is locally a sand-on-sand contact. Choosing a log marker to designate as the sequence boundary must rely on the biostratigraphy. Unfortunately, not all log and seismic sequences were resolvable with the graphic correlation tool. However, data terraces served to bracket sequences that are picked on the basis of seismic and well evidence (e.g. Sele sequences are correlated between the Top Forties and Balder Hiatal Intervals).

A basinal well 15 km to the east is interpreted in the same manner as figure 6 to correlate sequences and demonstrate how sediment distribution within sequences changes (figure 4.7). The Lower Balmoral sequence (2475 m and 2775 m) in figure 4.6 is a thick stack of sandy turbidites that becomes a thinner, silty interval in figure 4.7. The Maureen sequence sands of figure 4.7 between 8870 ft and 9130 ft are calcareous claystone in figure 4.6 (2850 m -
Fig. 4.7. - Graphic correlation and sequence stratigraphic interpretation of UK well 16/29-4. Data points are first downhole and acme occurrences of various taxa, distinguished by symbol. Paleobathymetry is given as bathyal and open marine for the entire section (paleobathymetry estimates courtesy S.P.T. - Robertson Research). Lithology symbols: 😼 = chalk, § = isolated limestones, ¶ = shale, = silt, = sand, = tuff.
2825 m). Additionally, the Top Forties terrace in figure 4.6 merges with the Upper Lista terrace in figure 4.7, demonstrating a longer stratigraphic break in the LOC of figure 4.7 at the top of the Upper Balmoral sequence. Individual biomarkers defining each sequence may vary slightly. Fossils that define a sediment pulse in one well may be found in hialtal intervals above or below the sequence in another well, but the markers should not define a sediment pulse for a different sequence (e.g. the acme of *Paleocystodinium bulliforme* (Ioannides, 1986) is within the sediment pulse of the Andrew sequence in figure 4.7, but occurs in the hialtal interval below the sequence in figure 4.6). Individual markers are found in different sequences if they occur out of normal succession (i.e. the LOC does not pass through them—see figure 4.3 for example). This is one advantage graphic correlation has over stratigraphic frameworks based solely on individual markers.

Plotting both graphs together with the same horizontal (time) scale highlights time-correlative stratigraphic breaks (figure 4.8). For example, 16/28-1 and 16/29-4 both show data terraces from 860 to 910 CSU. Both wells experience condensed sedimentation or erosion during that period, which demonstrates a correlative break in rock accumulation. Major breaks may contain more than one data terrace as shown at location A (figure 4.8). Even time intervals of small correlative breaks (i.e. location B, figure 4.8) identify depositional sequences, regardless of lateral facies changes. Figure 4.8 also brings out the variable nature of rock accumulation between the correlative terraces in time and space. In a submarine fan setting, sedimentation is complex and varies greatly in depositional rate along strike and dip (Walker, 1978). Where both wells share a time interval of no rock accumulation, the overlapping data terraces are interpreted to represent correlative events bracketing sediment pulses. Regional
Figure 4.8. Composite graph of line of correlations for two Central North Sea wells with overlapping time gaps indicated. Location A shows the collapse of two offsets into one and location B shows correlation of even short duration events (see text for further discussion).
correlation is necessary to verify that the stratigraphic breaks are basinwide events. Deposits between terraces do not necessarily have to overlap in time due to the episodic nature of the depositional setting. The different lengths of terraces between wells is explained by considering fan lobe avulsion and its effects on a LOC.

Tying the well data to a seismic line with synthetic seismograms is a critical step in supporting correlations, since seismic reflectors follow geologic time lines (Vail et al., 1977). Plotting the LOC of a well next to the time-converted gamma ray curve directly ties relative geologic time, as resolved by the biostratigraphy, to a seismic line (figure 4.9). This plot provides information concerning the variable duration of geologic time represented within the seismic section. Hiatal intervals correlate, within resolution limits, to regionally mappable seismic reflectors. Figure 4.9 illustrates that some intervals are below the resolution of this seismic data and are represented by a single wavelet peak or trough. These intervals are correlated on wells until a thicker section permits seismic resolution.

Sequences that are distinguishable on seismic data show remarkable lateral facies and thickness variation. Figure 4.10 illustrates how the seismic, well, and biostratigraphic correlations are integrated to resolve complex lobe deposition in two dimensions. The seismic line shows complex stratal termination patterns associated with deposits in a submarine fan setting (Posamentier et al., 1991). Correlations of well and biostratigraphic data help construct a sequence stratigraphic model highlighting the potential for multiple stratigraphic traps. Sandy turbidite depositional sequences, sourced from the west and depositionally pinching out to the east have considerable proven
Fig. 4.9. - Synthetic seismogram tie of the UK 16/28-1 well (Figure 4.6) to a regional seismic line. Graphic correlation and gamma log are time/depth converted to tie with the seismic data. This display illustrates how relative geologic time can be directly tied to seismic time. See Figure 4.6 for correlation of sequences as some sequences are below seismic resolution. (see text for further discussion).
Fig. 4.10 - Seismic and well log cross section between 16/28-1 and 16/29-4, illustrating the rapid lateral facies shifts that are seen in this area. Numbered sequence boundaries that start with $9_1$ (K/T boundary) on the interpreted seismic are displayed in the geologic cross section. Between sequences 3, 4, & 5 are additional sequences, identified and correlated on logs, highlighting the limiting seismic resolution when correlating surfaces. Seismic data courtesy of GECO-Prakla & Nopec.
reserves for various Paleocene sequences (e.g. Sarg and Skjold, 1982; O' Connor and Walker, 1993).

**Shelf to Basin Correlation of the Upper Paleocene and Lower Eocene**

The "top Palaeocene" seismic reflector is recognized by Rochow (1981) as a regional marker associated with the top of the tuffaceous claystones of the Balder Formation and the widespread coals of the Beauly Formation. This marker corresponds to the base of Stewart's (1987) Sequence 10, which is shown to be thin and at the limit of seismic resolution within the mapped area. The LAD of the dinocyst *Eatonicysta ursulae* (Morgenroth, 1966) marks the top of Sequence 10. Due to the high concentration of red-stained planktonic foraminifera, Stewart interprets this sequence as representing pelagic sedimentation similar to that recorded in the Røsnæs Clay of Denmark (Heilmann-Clausen et al., 1985), conditions brought about by high relative sea levels resulting from the collapse of the Paleocene Scottish uplift (Milton et al. 1990). The top of Sequence 10 represents a regional unconformity which is "baselapped" (Stewart, 1987) by younger Eocene sediments produced by renewed tectonism (Milton & Jones, in press; Galloway et al., 1993).

Interpreting the entire lower Eocene North Sea section as an interval of sediment starvation overlooks age-equivalent (*E. ursulae* palynomorph zone of Stewart, 1987) depocenters that are found in the Witch Ground Graben and Frigg field areas. Lower Eocene shelf deposits are penetrated in UK Quadrant 8 on the East Shetland Platform by the Shell/Esso 8/27a-1 well (figure 4.11). This well is important for two reasons: 1.) the Lower Eocene section has shallow water deposits and displays basinward shifts of facies; and 2.) biostratigraphy indicates that the shallow shelf deposits from approximately 2700 ft -2300 ft are
Fig. 4.11 - Composite plot of graphic correlation comparing the shelfal UK 8/27a-1 and basinal (Frigg Field) N 25/1-3 wells with overlapping LOC terraces from these wells and Figure 11 shown at the top.

Lithology key: \( \mathbb{C} \) = Cretaceous limestone, \( \mathbb{E} \) = isolated limestone, \( \mathbb{S} \) = sand, \( \mathbb{G} \) = silt, \( \mathbb{F} \) = shale, \( \mathbb{C} \) = coal. 1Paleobathymetry zones: 1. Transitional/Marginal marine, 2. Inner shelf, 3. Outer shelf, 4. Upper bathyal, 5. Middle to Lower bathyal (courtesy of S.P.T. - Robertson Research).
age-equivalent or younger than the Frigg deep sea fan (figure 4.11). Two
depositional sequences are recognized in the shallow water section of 8/27a-1,
which are below graphic correlation resolution between data terraces above the
Upper Forties and Balder sequences. The thick coals at 3100 ft and 2870 ft
represent the remains of a transgressive marsh, a zero base level datum, and
are found over a large region of the Outer Moray Firth Basin (Milton et al., 1990).
These coals are interpreted as deposits directly overlying sequence
boundaries. The coal at 3100 ft and the increasing-upward gamma ray sand
that is capped by a thin marine shale of the Middle Sele Sequence represent a
transgressive systems tract and maximum flooding surface in this well with the
decreasing-upward gamma sand being the highstand systems tract, the top of
which is a sequence boundary below the second major coal. Lowstand
deposits of this Middle Sele Sequence are seen in well N25/3-1, which has a
paleobathymetry in the upper bathyal (zone 4, figure 4.11) range. Age
correlation shows the Middle Sele Sequence in both sections to have rest on
chronologically-overlapping Top Forties terraces on each LOC. Directly
overlying the Middle Sele Sequence in the 8/27a-1 well is the second major
coal that is capped by mudstones containing the Balder Hiatal Interval.
Correlation to the deep basin reveals a thin unit above the Middle Sele
Sequence, but below the Balder Hiatal Interval. This additional sequence is
also unresolvable with graphic correlation, but is associated with a reported
acme occurrence of C. wardenense.

Although no major shift in paleobathymetry is indicated around 2720 ft in
8/27a-1 (zone 1 to zone 2), graphic correlation indicates a significant gap
associated with the acme occurrence of Inaperturopollenites spp., which is the
Balder terrace. Likewise, a data terrace around 2250 ft that has little
paleobathymetric evidence from fossils for a deepening is associated with the
top of *E. ursulae* - the same marker that caps the Frigg Fan (Heritier *et al.*, 1980).
Correlation of sections between these two chronologically-overlapping hiatal
intervals demonstrates that the shallow shelf deposits of 8/27a-1 from 2250 ft to
2720 ft are roughly the same age as the Frigg submarine fan (figure 4.11), and
define a lower Eocene regressive pulse. A more precise correlation is made
possible by sequence stratigraphic methods with the aid of graphic correlation.
The Frigg regression has been divided into three sequences in figure 4.11 with
a possible fourth sequence, Frigg-III, recognized by Mudge and Bujak (in press),
which appears to correspond to the upper sequence of the Tay Fan in UK Quad
21 (Den Hartog Jager *et al.*, 1993). The Lower Frigg Sequence is characterized
by the tops of dinocysts *D. oebisfeldensis* and *Dracodinium solidum* (Gocht,
1955) The top of this sequence is a minor terrace here associated with
*Dracodinium politum* (Bujak, *et al.*, 1980). Graphic correlation comparison
suggests that this sequence is missing in 8/27a-1. The Middle Frigg Sequence
is picked on the N25/1-3 well at the base of a thick sand near the top of the Frigg
fan. This sequence contains the tops of *Spiniferites septatus* (Cookson &
Eisenack, 1967), *Apectodinium summissum* (Harland, 1979) and starts at the
top of *Dracodinium varielongitudum* (Williams & Downie, 1966). By graphic
correlation, this sequence is equivalent to the lower part of the section between
the Balder terrace (2720 ft) and the Top Frigg terrace (2250 ft) in 8/27a-1. The
top of this sequence in N25/1-3 occurs near CSU 810. When the 810 CSU
value is plotted on the line of correlation for 8/27a-1, its depth value intersects
the well at approximately 2650 ft. A thin glauconitic sand is found at this depth in
the well and marks the top of the Middle Frigg Sequence in 8/27a-1, even
though none of the diagnostic marker fauna for the sequence were found.
Conversely, the Upper Frigg Sequence in 8/27a-1 has diagnostic forms of *Kisselovia edwardsii* (Wilson, 1967) and the acme occurrence of *Homotrybium tenuispinosum* (Davey & Williams, 1966), which occur in a single sample that also has the top *E. ursulae* at the top of the Frigg section in N25/1-3. This grouping of markers in one sample suggests that the Upper Frigg Sequence found in 8/27a-1 is missing in N25/1-3. Graphic correlation demonstrates a longer Top Frigg terrace in N25/1-3 than in 8/27a-1, indicating a longer time gap in the basinal well.

*Nested stratigraphic cycles on seismic and in graphic correlation*

Recognition of a lower Eocene shelf in seismic data from the Outer Moray Firth area is complicated by the presence of high amplitude, discontinuous reflectors that represent the coaly coastal plain deposits of the Beauly Formation. These sediments also represent the transgressive phase of the upper Paleocene-lowermost Eocene regression/transgression cycle that thickens to the west. A single seismic line in the east-central part of Quadrant 14 (figure 4.12, see figure 4.1 for location) displays a distinct progradational package downlapping onto the Beauly coal reflectors. Tracing this package to adjacent lines, these sediments fill erosional topographic lows in the Beauly seismic facies. The top of the prograding wedge and its lateral equivalent is a major downlap surface for the next regressive pulse in the middle Eocene, and likely represents the top of Stewart Sequence 10. The wedge and time equivalent sediments downlap and onlap the Beauly and are traced with well control to condensed (hiatal) intervals that cap these lowermost Eocene coals. Where this drape facies is found, the middle Eocene regression directly downlaps onto the Beauly seismic package or its time-equivalent Balder reflector.
Fig. 4.12 - Seismic expression of the mid-Lower Eocene regressive shelf. Labeled features are: A. Upper Balmoral sequence, B. Upper Forties sequence, C. Middle Sele sequence, D. Upper Sele sequence, E. Main Balder sequence, F. Frigg Regression (undifferentiated), G. Nauchlan sequence, H. Lower Lark 1 sequence. Stratigraphic terminations are highlighted with small arrows - . Note the backstepping units within the Balder sequence separated by a transgressive surface (dashed line --- ). Third order boundaries = — , second order boundaries = ———. Seismic data is shown courtesy of SPT(Horizon Geophysical).
A striking feature of figure 4.12 is the throughgoing reflector (trough) just above 1.0 seconds. This marker represents a coaly section above the base Balder sequence boundary. The Balder sequence has internal downlap surfaces indicating the backstepping of sediment packages and the transgressive nature of this sequence. Above the backstepping units is a strong reflector that is onlapped and downlapped by the thin prograding package. When traced to wells with biostratigraphic reports that are tied to seismic by synthetics, this reflector corresponds to a mudstone representing a rapid deepening (inner/outer shelf to upper bathyal in one sample interval) and a graphic correlation terrace (Balder hialtal interval).

This small scale shelf has a facies distribution similar to the more extensive Paleocene-lowermost Eocene shelf. Note the high amplitude peaks at the left of the prograding package that lose strength moving right. These seismic facies are interpreted as a coastal plain (left) to shoreface/mouth bar (right) transition, mirroring similar transitions within the Beauly and progradational Dornoch Formation. For this reason, care must be taken when picking the "top Palaeocene" reflector to insure proper chronostratigraphic correlation. Even when depositional dip lines are used, this pick is made possible only by directly tying the biostratigraphic data to seismic with synthetics.

Other wells in UK Quadrant 15 also encounter lower Eocene deep water sands and silts that are capped by a marker shale (Top Frigg hialtal interval) containing the LADs of *E. ursulae* and *Hystrichosphaeridium tubiferum* (Ehrenberg, 1838) and overlie another marker shale (Balder hialtal interval) with acme occurrences of *D. oebisfeldensis* and *Inaperturopollenites spp*. Figure 4.13 is a cross section through this depocenter in the Witch Ground Graben.
estimates are from S.P.T. (Roberson Research).
Eocene section (see text for discussion), Paleodepthymetry
depths, with UK 15/6-1 having an inner shell. Upper Middle
next two regressions are deposited in outer shell/upper bathyal
Paleocene shallows to inner shell and transition.

Lower Paleocene pulse is bathyal, while the Upper
multisequence regression pulses, Paleodepthymetry of the
highlight the second order transgressions that bracket
three of the five logs, the detailed biostratigraphic reports
for location. A composite graphic correlation display of
Ground Graben area of the Central North Sea (see Fig. 4.1
Fig. 4.13 - Stratigraphic cross section through the Witch

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Composite graphic correlation plotting demonstrates two major hialtal intervals bracketing a Ypresian sediment pulse. Correlation lines through the cross section indicate depositional sequences that are carried with and between the overlapping terraces on graphic correlation. The cross section highlights major transgressive/regressive cycles that bundle depositional sequences. Regressive phases represent most of the sediment and transgressive phases represent major hialtal intervals (Lista, Balder, Top Frigg, and Upper Eocene). Well 14/20-22 in the cross section ties to the seismically identified shelf of Figure 4.12 just downdip of the prograding package. Correlation to the other wells demonstrates the position of this wedge between the Balder and Top Frigg terraces.

**Correlation to NW Europe Outcrops and Boreholes**

Tying sequence boundaries in the Central North Sea to outcrop sections and cored boreholes in Northwest Europe is a critical step in testing and refining a paleogeographic model for the entire Paleogene North Sea Basin. The first step toward this goal required a good biostratigraphy tie of the Central North Sea to outcrops and boreholes described in NW Europe. The best place to start this tie is the Danish/North German section, as it consists of mainly deep water marls and claystones with a highly detailed dinoflagellate and nannofossil stratigraphy (Heilmann-Clausen *et al.*, 1985; Michelsen *et al.*, in press). Using the mature composite standard built in the Central North Sea, data was graphed from the Viborg 1 borehole (Heilmann-Clausen, 1985), the D.G.I. 83101 Østerrenden borehole (Nielsen *et al.*, 1986) and the Wursterheide borehole (Heilmann-Clausen and Costa, 1989). Bases (FADs) of fauna are added to the plots to improve resolution and incorporate additional information. Bases in the North Sea composite standard are carried as the lowest (oldest) downhole
appearance of any particular fossil. Generally, bases are an unreliable
stratigraphic tool in areas where ditch cuttings are the primary data source
because of the problems of cavings. Lines of correlation are drawn mainly with
respect to faunal LADs, as is the case in the North Sea, for consistent
correlations to the Central North Sea.

Østerrenden borehole

The first borehole graphed using the Central North Sea Composite
Standard is the Danish Geotechnical Institute 83101 borehole (Nielsen et al.,
1986) at Østerrenden (see figure 4.1 for location). The line of correlation is
interpreted with six data terraces (figure 4.14). The chronological position of
some of the overlapping hiatal intervals from North Sea wells is included in
figure 4.14 to relate Østerrenden terraces to the subsurface framework. A good
overlap correlation appears for five of the terraces with a possible overlap on
the sixth. The Top Frigg correlation is less reliable due to its occurrence within
the last sample, as fossil ranges may extend upwards in a more complete
section. As the top of *E. ursulae* is indeed the LAD of this marker in Denmark
(Nielsen et al., 1986 - p. 247), perhaps the Top Frigg terrace is correlated
correctly. With this correlation, depositional sequences from the North Sea can
be tentatively tied to the section described by Nielsen et al. (1986). Key surfaces
are difficult to locate in the section and are sometimes ambiguous with respect
to sequence stratigraphic methodology. Glaucocitic intervals described near the
top of the Haslund member of the Ølst Formation (118 mbsl) and the informal
Glaucocite Silt member (133-136 mbsl) are interpreted to represent very slow
marine sedimentation and may represent maximum flooding events or
highstand periods. The dinocyst *Apectodinium augustum* (Harland, 1979),
appears just above the sharp top contact of the Glaucocite Silt member and this
Fig. 4.14. - Graphic correlation of the dinoflagellate stratigraphy from the D.G.I. 83101 borehole at Østerrenden. Overlapping data terraces from the Central North Sea are plotted at the top for comparison. Lithology column and formations come from Nielsen et al. (1986), depositional sequences are named by their age-equivalent units in the Central North Sea (see text for further explanation).
FAD helps define a data terrace that overlaps with the Mid-Balmoral terrace in the basin. Likewise, the top of *A. augustum* marks another terrace that overlaps with the Top Forties Hiatal Interval in the basin. A reported concretion layer that may also represent sediment starvation occurs at this boundary.

The glauconitic horizon at 118 mbsl in the Østerrenden borehole likely represents a stratigraphic gap, but is unresolvable with graphic correlation. The occurrence of more abundant *C. wardenense* and *D. oebisfeldensis* above this layer suggests a correlation with the Upper Sele depositional sequence, which is also unresolvable in the North Sea with graphic correlation (see figure 11). The overlying Værøm member with volcanic tuff layers correlates laterally to the Fur Formation (Heilmann-Clausen *et al.*, 1985) and is widely accepted as the equivalent of the Balder Tuff in the North Sea (Knox and Harland, 1979; Knox, 1984; Morton and Knox, 1990). Graphic correlation confirms this tie as the Østerrenden borehole displays a major terrace at the Røsnæs Clay/Værøm member boundary, which overlaps the Balder Hiatal Interval in time. Nielsen *et al.* (1986) recognize this contact as an unconformity with burrowing and as a condensed R1-R3 unit. Interpreting the remainder of the Røsnæs Clay Formation and the overlying Lillebælt Clay is very difficult. The top of *H. tubiferum* occurs much lower than expected, and the introduction of other key markers such as bases for *Areosphaeridium diktyoploks* (Klumpp, 1953) and *Dracodinium pachydermum* (Caro, 1973) and a low top of *Kisselovia coleothrypta* (Williams & Downie, 1966) present correlation problems between the Central North Sea and Denmark. Two interpretations are presented. The terraced line honors the top of *H. tubiferum*, which is usually found in the basin near the top of *E. ursulae*, and places a large stratigraphic gap within unit R6. This interpretation places the Lillebælt Clay as age-equivalent to a large part of
the Top Frigg Hialtal Interval, and is evidence for the partitioning of sediment to
the outcrop sections during times of sediment starvation in the Central North
Sea. The second interpretation ignores the top of *H. tubiferum* and considers it a
"depressed" top (see above), honoring instead the top of *S. septatus* and the
base of *D. pachydermum*. This interpretation is more conservative, and is
preferred after examining other boreholes that have *H. tubiferum* lower than
predicted.

The deepest biostratigraphic boundary for this borehole occurs within the
Holmehus Formation. A sequence boundary is picked solely on the
biostratigraphy and equated with the Lower Balmoral/Upper Balmoral break in
North Sea wells. This terrace corresponds to the upper part and boundary of
dinoflagellate zone 4 in the Viborg borehole (Nielsen *et al.*, 1986, p. 246), and is
an example of an inferred correlation where little evidence for a stratigraphic
break exists in the rocks. This correlation helps carry the stratigraphy as a tie for
North Sea biostratigraphy to the outcrop sections. The importance of this type of
correlation is illustrated by a graph for the Viborg borehole (figure 4.15).

*Viborg borehole*

The Viborg borehole (see figure 4.1 for location) encountered Paleogene
sediments from the Røsnæs Clay down to Danian Limestone (Heilmann-
Clausen, 1985). This borehole is critical in tying a nannofossil stratigraphy of
NW Europe to the graphic correlation stratigraphy of the Central North Sea. The
nannofossil tie comes from a correlation of Viborg dinoflagellate zones within
the stratigraphic framework of Michelsen *et al.*, (in press), which tied nannofossil
zones to the dinoflagellates indirectly through correlation with other European
basins (Heilmann-Clausen, pers. comm.). Nannofossil zones are very difficult to
identify with cutting samples since most standard NP zones are based on FADs
Fig. 4.15. - Graphic correlation plot of dinoflagellate stratigraphy from the Viborg borehole (Hellmann-Clausen, 1985). Nannofossil correlations come from the stratigraphic framework of Michelsen et al. (in press), correlated to Viborg dinoflagellate zones. Overlapping data terraces from the Central North Sea are plotted at the top for comparison (see text for further discussion).
(Martini, 1971), however, nannofossil stratigraphy is presently the most complete correlation framework in NW Europe (Aubry, 1986; Aubry et al., 1986).

Figure 4.15 displays how the North Sea terraces relate to nannofossil zones and the older deposits not encountered in the Østerrenden borehole. A good correlation is achieved with the Balder, Top Forties, Mid-Balmoral, and Upper Lista Hiatal Intervals and the Viborg line of correlation. Additionally, the Base Balmoral terrace is well developed at Viborg, correlating to a level near the base of the Holmehus Formation. It is possible that this terrace is “artificially” long (see discussion above), however, as it occurs at the base of an 8 m thick barren interval. The Upper Maureen terrace probably correlates within the sample gap between the Kerteminde Marl and Danian Limestones. This presents an interesting correlation where Danian limestones are age-equivalent to clastic fan deposition of the Maureen sequence in the Central North Sea.

Whitecliff Bay section

The Eocene succession at Whitecliff Bay on the Isle of Wight (see location, figure 4.1) has been described in detail with calcareous nannofossil studies by Aubry (1983, 1986), dinoflagellate cyst stratigraphy by Eaton (1976), and the sedimentologic work of Plint (1983). The sequence stratigraphic study of these outcrops by Plint (1988), correlates to the eustatic curve of Haq et al. (1987), and achieves a good fit. To compare this work with our current study, the dinoflagellates of Eaton (1976) were graphed against the composite standard used in the North Sea and Denmark. The resulting plot and interpretation is shown in figure 4.16.

Sequence stratigraphic interpretation of this section is modified from Plint (1988), by correlating sequences described in other basins and using the original depositional environment descriptions of Plint (1983). Sequences at
Fig. 4.16. - Graphic correlation plot of the dinoflagellate stratigraphy from Eaton (1976) of the Bracklesham succession at Whitecliff Bay. Lithologies and depositional environments are modified from Plint (1983), as is the sequence stratigraphy (Plint, 1988). Nannofossil picks come from Aubry (1983, 1986). Magnetostratigraphy (agnet = normal polarity) comes from Townsend & Hailwood (1985) and Aubry et al. (1985). Overlapping data terraces from the Central North Sea are plotted at the top, demonstrating the difficulty of correlation with the Central North Sea (see text for further explaination).
Whitecliff are related to Central North Sea sequences by graphic correlation. Fisher Bed I is correlated to the upper part of the Middle Frigg sequence in the basin. The Middle Frigg sequence is split into two sequences onshore with the Portsmouth sand in London Clay Division D (King, 1981; Plint, 1988-not shown in figure 4.16) being the lower part. Two possible interpretations are presented for Fisher Bed I. If the tops of Dracodinium condylos (Williams & Downie, 1966) and Dracodinium simile (Eisenack, 1954) are honored, a large amount of section falls within the Intra-Frigg Hital Interval when correlating to the basin. If the bases of Samlandia chlamydophora (Eisenack, 1954) and A. diktyoplokos are honored, the correlation of this section to the basin requires an additional sequence. For consistency in correlation to the basin, we have chosen to honor the tops in this instance. Interpretation of the section from upper Fisher Bed IV through Bed V is very difficult. The position of a terrace at the base of Fisher (1862) Bed V is strongly influenced by the recognition of a biostratigraphic and magnetostratigraphic gap at that horizon (Aubry et al., 1986). This hiatus is correlated to a major eustatic fall at the top of the Ypresian, "49.5 Ma" on the Haq curve (Aubry, 1991; Plint, 1988; P.R. Vail, pers. comm.). Intuitively, the Lower Eocene Frigg regression in the North Sea should tie to this globally-recognized major sea level fall, yet graphic correlation shows that this event is younger than the main Frigg sands (see figure 4.11). It is believed that the major short term sea level falls documented globally for this time (Aubry, 1991; Haq et al., 1988) are subdued in the North Sea due to long term sea level rise with deposits from this major fall appearing locally in the North Sea (Upper Frigg sequence). The bed at the top of Fisher IV has NP 13 fossils (Aubry, 1983) and the base Fisher V event correlates with the Upper Frigg Sequence or Frigg-III Sequence recognized by Mudge & Bujak (in press). The base Fisher V
sequence boundary may correlate to the deeply incisive sequence in the 23.1
zone of Den Hartog Jager et al. (1993), but is difficult to place within our
subsurface framework. The high amplitude seismic reflector below the Top
Frigg Hiatal Interval shows considerable erosional topography in the shelfal
areas of UK Quadrants 14 and 15 that may be related to a fall in sea level,
however, the Upper Frigg Sequence is thin in most parts of the basin.

Sequence interpretations are made based on basinward shifts of facies,
where shallow water sediments rest directly on deeper ones, indicating a sea
level fall. The Whitecliff section records many more such events than are
resolved with graphic correlation. Some of these sequences correlate in time to
hiatal intervals of sediment starvation in the North Sea (Fisher Beds I, XIX, II-
IV?). This correlation suggests two points: 1.) outcrop sections in Europe can
correspond to data terraces in the North Sea biostratigraphy and probably are
the highstand and transgressive systems tracts equivalents of high gamma
shale drapes in the basin; 2.) more sequences are described in outcrop than
are documented in the basin. This second point emphasizes the importance of
integrating both outcrop and subsurface data sets to build a complete sea level
history for the North Sea and its connected NW European basins.

*Wursterheide borehole*

Recognition of sequences in deeper water sections without obvious
facies shifts is accomplished with electric log data and grain size analysis. This
information, combined with biostratigraphy, aid in the recognition of more subtle
boundaries. These subtle boundaries are recognized in Ieper clay sections of
Belgium (Vandenberghhe et al., 1988). The Northern Germany section,
represented in boreholes is similar in this respect. The Wursterheide borehole
(figure 4.17-see figure 4.1 for location) cored a thick lower Eocene silt/clay
Fig. 4.17. - Graphic correlation of dinoflagellates in the North German Wursterheide borehole from Hellmann-Clausen and Costa (1989). In this section, the overlapping "Balder" LOC offset from the North Sea corresponds to an interval of deposition. Interpretation of gamma ray log identifies depositional sequences that are observed elsewhere in Northwest Europe.
section with extensive dinoflagellate cyst recovery (Heilmann-Clausen and Costa, 1989). The Lower Eocene section from 570 meters to 720 meters has one of the best defined LOC's in the basin. Most of this section would normally fall within the Balder hialtal interval in the Central North Sea (figure 4.17). Subtle increases and decreases in gamma ray value represent changes in silt and organic content interpreted as indications of sea level change. By correlating the biostratigraphy, these gamma ray trends are related to shallow water age-equivalent deposits where sea level change is more noticeable. Sequence names come from correlative formations in the London-Hampshire and Belgium Basins. Correlation of the LOC for the labeled Lower and Middle Frigg sequences in the Wursterheide well compares favorably with the Frigg section in N25/1-3. Numerous Dracodinium species are observed in both localities, providing a direct tie. A minor terrace may be interpreted at approximately 615 meters well depth between D. simile and D.-solidum similar to one seen in well N25/1-3 (see figure 4.11), which corresponds to the maximum flooding surface of the Christchurch/Lower Frigg Sequence at Wursterheide. At 571 meters well depth, however, a major data terrace develops that can be linked to a gamma ray marker. This terrace overlaps with the Intra-Frigg hialtal interval of the Central North Sea, but is also slightly older than the overlap interval observed from other wells. Ties to dinoflagellate zones places this gap in the upper part of zone D 8 (IGCP #124 Subgroup-Vinken, 1988) since the top of A. summissum occurs with the base of S. chlamydophora, and the base of A. diktyoplokos is in the next sample. When correlated to the Belgium section, this gap covers two sequences, the Egem and Kortemark, as the base of S. chlamydophora occurs within the Kortemark and the base of A. diktyoplokos occurs in the Egem sands above (DeConinck, 1990). Here, a datum top occurs with these bases to provide
a more secure correlation with the Central North Sea. If this hiatus is due to sediment starvation resulting from a deepening, then sediments above the hiatus may represent a lowstand depositional pulse similar to the Central North Sea. The coarsening upward gamma signal becomes a lowstand prograding wedge that correlates in outcrop to the Egem Stone Band/Merelbeke clay layer above the Egem sand. The Merelbeke clay is interpreted as very shallow deposits with fresh water influence (Steurbaut & Nolf, 1986), and represents marginal marine transgressive deposits above the sequence boundary at the top of the Egem. The fining upward silt from 540 to 525 meters in the Wursterheide well then becomes the transgressive systems tract, and the coarsening upward section from 525 to 503 meters is then the highstand systems tract (Pittem clay equivalent). The sharp change in the gamma log above 503 meters consequently belongs to the Vlierzele sequence, which has also been related to the “49.5 Ma” sea level fall (De Baptist et al., 1989; P.R. Vail, pers. comm.) of Haq et al. (1987). The line of correlation for the section from 503 to around 430 meters compares well with a similar line within the Upper Frigg Sequence of UK 8/27a-1 (figure 4.11).

**Chronostratigraphic summary section**

When information from as many sources as possible is integrated, a chronostratigraphic chart for all basins studied is built (figure 4.18). This correlation chart provides insight into paleogeography of the time slice studied, relating basinal lowstand deposits to shelfal transgressive and highstand ones. Comparison of events documented in this study to those predicted by the Haq et al. (1988) curve demonstrates that a eustatic signal can be identified in northwest Europe, but that additional cycles are required to fully describe the sections. The eustatic curve has been modified here by matching the
Fig. 4.18. - Chronostratigraphic chart for Northwest Europe for deposits of Selandian to Lutetian age. Paleogeographically, lowstand deposits in the Central North Sea correspond to sequence boundaries in outcrop sections and marine hiatal intervals in the basin tie to multi-sequence outcrop sections. *Missing section may be caused by wave base erosion or subaerial exposure during sea level fall, or tectonic uplift (especially in the Thanetian section of the Central North Sea).

1 - Revised time scale from Cande & Kent (1992), with nannofossil correlations from Aubry et al. (1988) - part of Hardenbol et al. (in prep.)

←New (O & SS) = position of a sequence boundary from outcrop and subsurface data not picked in Haq et al. (1988)←

←New (O) = position of a sequence boundary from outcrop data not picked in Haq et al. (1988)

Lithology and Facies key
Dominantly-Sand Turbidites Transgressive Shoreface/Estuary Sands
Dominantly-Silt Turbidites Erosion or Missing Section* Incisive SB
Hemipelagic Mud/Marine Hiatus Graphic Correlation Data Terrace Tuff
Shell Beds Marginal marine carbonate Sequence Boundary (SB)
Highstand Silt/Sand Nonmarine Sand/Shale Estuarine/Lagoon Shales
Lowstand Prograding Glaucolite Offshore Muds Coal
Sand/Shale Transgressive Surface

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### Outcrop Sequence and Formation Correlations

<table>
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<th>Danish Sub-basin</th>
<th>Belgium</th>
<th>Isle of Wight/London-Hampshire</th>
<th>Paris Basin</th>
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<td>Liliebaai clay</td>
<td>D9</td>
<td>Vleterse</td>
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<td>D8</td>
<td>Zeebrugge</td>
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<tr>
<td></td>
<td>Pelm</td>
<td>Ostend</td>
<td>Fisher Beds 8 &amp; 9</td>
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<td>Kortemind</td>
<td>Asleba</td>
<td>Portsmouth</td>
</tr>
<tr>
<td></td>
<td>Pelm</td>
<td>D7</td>
<td>London &amp; Hastings</td>
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<td>D6b</td>
<td>Cheshunt</td>
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<tr>
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<td>Kortemind</td>
<td>D5b</td>
<td></td>
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</table>

**Eustatic Curve**

Modified from **aq et al., (1988)**

**Legend**

- High sea level
- Low sea level
- New (O)
- New (O & SS)
nannofossil zones of Haq et al. (1988) to those of Aubry et al. (1988), correlated to the revised magneto-chronostratigraphy of Cande and Kent (1992). Nannofossil zones are correlated to planktonic foraminifera zones (J. Hardenbol & W.A. Berggren, pers. comm. 1994), which provide the true link of biostratigraphy to magnetostratigraphy, therefore these correlations should be regarded as tentative until a revised correlation of nannofossils to foraminifera is published for the new time scale.

Units that appear continuous in outcrop (e.g. London and Ieper Clay Formations) may actually contain bypass surfaces that are shown as missing section in figure 4.18. These intervals are necessary to place Central North Sea lowstand deposits into a chronostratigraphic framework with NW Europe outcrops. An alternate possibility is that outcrop sequence boundaries are Type 2 (Van Wagoner et al., 1988), with no lowstand, but the same sequence boundary is Type 1 in the North Sea due to enhancement by tectonics (Vail et al., 1991). This problem simply reemphasizes the dangers of separating sea level change magnitudes without considering the interaction of long and short term cyclic conditions.

**Discussion**

The key to establishing a reproducible sequence stratigraphic framework is good age control (biostratigraphy, magnetostratigraphy, isotope stratigraphy, etc.). Recent publications highlight of the complex problem of verifying the age-equivalence of key bounding surfaces (Hardenbol, 1992; Aubry, 1991), and the observation of depositional sequence-forming mechanisms at different time scales (Posamentier et al., 1992a). In Northwest Europe, construction of a surface-based stratigraphy is difficult because of there are more key surfaces than biostratigraphic zones. The most recent biostratigraphic zonations are very
high resolution and have greatly enhanced correlations (e.g. Jolly, 1993), however, biostratigraphic zones do not represent physical surfaces in the rocks and multiple arise when correlating deep marine biostratigraphy to shallow sections. Certain key markers may be environmentally-controlled or subject to reworking, which introduces another possibility of correlation error. Correlation by biozones based mainly on FADs, although the most common practice onshore, is often at odds with correlation by key markers (usually LADs or acme occurrences), the most common practice in the North Sea. Good examples of this problem are the placement of the top *H. tubiferum* marker, which falls within the Top Frigg Hiatal Interval in the basin but occurs in older rocks in outcrop, and the base of *D. pachydermum*, which is carried lower in the North Sea composite standard than its proper relative position in outcrop correlations.

These examples illustrate the need to combine basinal marker correlation and outcrop zonal correlation. Graphic correlation is a hybrid between the two systems and attempts to capture the best feature of each. It has the potential to isolate problems in the biostratigraphic data due to reworking or environmental factors while adding a chronological control that is beyond most zonal schemes. Overlapping data terraces is the best available way to establish chronological correlations, even though the interpretation of a line of correlation and its complexity may be non-unique. Graphic correlation is preferred over the condensed section approach in the North Sea basins where depositional rates are relatively low. The condensed section approach is most successful identifying intervals of slower than normal sedimentation in basins where general deposition rates are high. For example, in the Gulf of Mexico, condensed sections over 300 ft thick have been published (see examples from Armentrout and Clements, 1991 - figures 3 & 4). These sections should be
referred to as "relatively condensed" if the sedimentation rate exceeds the <1 cm/ky proposed by Loutit et al., (1988). The Central North Sea Paleogene section has a punctuated sedimentation history with slower depositional rates. Correlation within the Central North Sea Paleogene requires a different biostratigraphic approach than the methods used in the Gulf of Mexico. Using a chronostratigraphic framework of terrace-bounded units, this study produces a sequence stratigraphy for northern European basins, based on correlation of key bounding surfaces, recognizing nested cycles and providing insight into paleogeographic changes from shelf to basin.

Chapter Conclusions

By integrating seismic, well log, outcrop, and biostratigraphic data, we show how a sequence stratigraphic model may be built for a basin once a solid chronostratigraphic framework is in place using the graphic correlation method. Our conclusions on the stratigraphy of the Paleogene for the North Sea and NW Europe are that sedimentation in the Central North Sea occurs as a series of punctuated depositional pulses separated by time-correlative biostratigraphic data terraces, referred to as hiatal intervals. However, not all sequence boundaries that are observable in the physical stratigraphy are resolvable by graphic correlation, but the method serves to bracket packages that are defined in outcrop, by seismic, or by well log interpretation. When sequence stratigraphic interpretations of outcrop and borehole sections from NW Europe are incorporated into the chronostratigraphic framework of the Central North Sea, a genetic link between the shallow and deep sections is proposed, which assists in the development a paleogeographic and geologic depositional model for the study area.
Chapter 5
Summary of Conclusions

The usefulness of a stratigraphic analysis can be measured by asking two questions; (1) is it reproducible and understandable, and (2) does it bring a fresh view of previously published stratigraphy. This study can certainly answer yes to the second question and hopefully yes to the first. The integration of graphic correlation and sequence stratigraphy in basin stratigraphic analysis is a new approach as no model currently exists outside this thesis to position and interpret graphic correlation terraces within a depositional sequence. Graphic correlation has been used to identify large scale chronostratigraphic units and to correct isotope curves in the literature, but it has not been applied to sequence stratigraphic problems. This procedure is best used in areas with a wealth of biostratigraphic or other chronostratigraphic data, however, this does not preclude its usefulness in areas of sparse data. A knowledge of the possible complications in a well-studied basin serves to caution correlations in areas with less information. Forewarned is forearmed as data resolution limits will control the degree of confidence in a chronostratigraphic correlation. The integration of graphic correlation and sequence stratigraphy bridges the gap between biostratigraphic zonal correlations, which do not account for key bounding surfaces in the rock, and pure sequence stratigraphic correlations, which often infer the synchronaeity of a unit without necessarily documenting it with biostratigraphy.

In this study, a high frequency ("third order") sea level signal can be documented and correlated through many different depositional environments with a consistent biostratigraphy. Thirty third order cycles are documented by examining subsurface and outcrop data around NW Europe. These cycles are
correlative in time but have differences in expressed magnitude, depending on their position within a low frequency cycle. Five low frequency ("second order") sea level cycles are also observed, which vary in magnitude and phase depending on sub-basin location throughout NW Europe. Low frequency events are not the most reliable chronostratigraphic units for correlation outside a given tectonic provenance due to local complications and interference by the high frequency signal. The high frequency sea level signal documented by this study recognizes all the eustatic events of Haq et al. (1988) with the addition of seven new cycles not documented on the Haq curve. The high frequency signal resolved from subsurface data correlates well with the framework of Den Hartog Jager et al. (1993). Lithostratigraphic and previously published sequence frameworks have also been correlated to the depositional sequence framework of this study. A consistent tie was difficult to achieve due to differences in lithostratigraphic and sequence stratigraphic methodologies, however, a key is provided that relates lithostratigraphic units to their range of depositional sequences. Lithostratigraphy and sequence stratigraphy will remain mutually exclusive, but complimentary stratigraphies in NW Europe.

The depositional systems of the North Sea are controlled by second and third order sea level cycles as well as sediment source and supply, depositional profile, and differential compaction subsidence. The second order cycles represent a reorganization of the depositional system and are comprised of multiple third order cycles. Third order cycles control the distribution of lithofacies and individual reservoir and seal rocks in the basin. Their character is a function of position within a second order cycle. They are correlated within a framework of hialtal intervals identified from graphic correlation. The depositional profile controls the distribution and expression of depositional
systems tracts and the paleogeographic model. In the Central North Sea, a variation of the classic Vail model is proposed, which accounts for the lack of significant transgressive and highstand systems tracts. Differential compaction subsidence creates space for sediments, and suggests relative time represented by deposition and hiatus.

Hiatal interval is a term introduced to account for error bars in data collection and also to suggest an alternative to condensed section terminology. Hiatal intervals of this study are thin units of rock that are identified with graphic correlation terraces. The differences between hiatal intervals and condensed sections are: (1) an assumption that sedimentation in "condensed" units is not continuous, that multiple hiatal surface exist, requiring detailed biostratigraphic sampling to identify, and (2) hiatal intervals can expand into section that contains multiple depositional sequences. The first point has been documented by Aubry (1991) and is supported by many published articles that examine the discontinuity of the rock record. The second point is documented in this study, where major Central North Sea graphic correlation data terraces expand into thick sections in NW Europe containing multiple depositional sequences. Hiatal interval correlation provides a chronostratigraphic framework that can be further expanded with more detailed work on the hiatal intervals themselves.
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  G.C. St. C., Posamentier, H.W., Ross, C.A., & Van Wagoner, J.C. (eds.), Sea-
  level changes: An Integrated Approach. SEPM, Tulsa, Special Publication 
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## Appendix Table 1 - Biostratigraphic datums from well N16/1-1.

*Courtesy of S.P.T. (Robertson Research)*

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