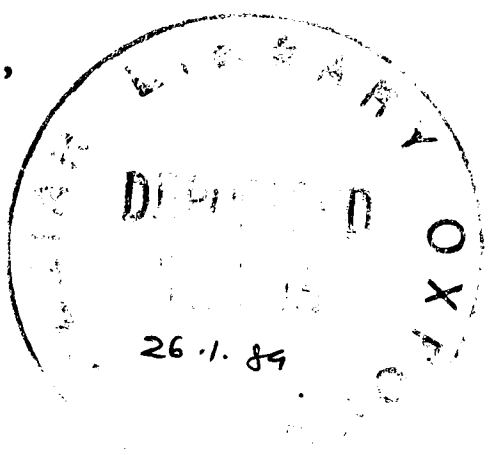
A SEISMIC INTERPRETATION OF THE DANISH NORTH SEA.

D.Phil Thesis

Department of Earth Sciences,

University of Oxford.



Hilary, 1988.

Volume 1: Text.

JOSEPH ALBERT CARTWRIGHT

WOLFSON COLLEGE,

OXFORD.



Frontispiece; An impression of the beginnings of the North Sea Rift.

This Thesis is dedicated in memory

of my father, Albert Cartwright.

"There was a whispering in my hearth,
 A sigh of the coal,
Grown wistful of a former earth
 It might recall.

I listened for a tale of leaves
 And smothered ferns;
Frond-forests: and the low, sly lives
 Before the fawns.

My fire might show steam-phantoms simmer
 From Time's old cauldron,
Before the birds made nests in summer,
 Or men had children.

But the coals were murmering of their mine,
 And moans down there
Of boys that slept wry sleep, and men
 Writhing for air.

And I saw white bones in the cinder-shard,
 Bones without number;
For many hearts with coal are charred,
 And few remember.

I thought of some who worked dark pits
 Of war, and died
Digging the rock where Death reputes
 Peace lies indeed.

Comforted years will sit soft-chaired
 In rooms of amber;
The years will stretch their hands, well-cheered
 By our lives' ember.

The centuries will burn rich loads
 With which we groaned,
Whose warmth shall lull their dreaming lids,
 While songs are crooned.
But they will not dream of us poor lads,
 Lost in the ground."

'Miners'
Wilfred Owen.

"It is a popular delusion that the scientific enquirer is under an obligation not to go beyond generalisation of observed facts...but anyone who is practically acquainted with scientific work is aware that those who refuse to go beyond the facts rarely get as far."

Professor J.W.Gregory.

ABSTRACT

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Thesis submitted for the degree of Doctor of Philosophy, Hilary 1988.

A Seismic Interpretation of the Danish North Sea.

This study is based on a regional grid of seismic data acquired by Merlin Geophysical. The main emphasis of this thesis was on the detailed structural mapping of the Danish Central Graben, since this area has the highest density of well and seismic data. The principal objective of the study was to explain why the North Sea Rift changes strike in the Danish Sector, from the N-S trending Dutch Central Graben, to the NW-SE trending U.K/Norwegian Central Graben.

The Danish Central Graben opened initially in the Late Carboniferous, as part of a regional dextral transtensile deformation that affected much of Europe. The initial extensional structures developed by reactivation of a pre-existing basement fabric. The NNW trending Coffee Soil Fault bounding the rift, is interpreted as a planar structure transecting the entire crust, and is thought to have developed by extensional reactivation of an east-verging Caledonian thrust. Basement shear zones identified on the rift shoulders on the Ringkobing-Fyn High are interpreted as the along-strike continuation of the Caledonides of Southern Norway, offset to the east by syn-orogenic transform motion along fracture zone elements of the Tornquist Zone. The WNW trending fault zones that dominate the structural grain in the Danish Central Graben are shown to be closely related to WNW trending fracture zones on the Ringkobing-Fyn High, which are regarded as splay shears of the Tornquist Zone.

The WNW trending transverse fault zones segment the Danish Central Graben. The segmentation exerted a fundamental influence on the structural and stratigraphic development of the rift, in that individual segments were free to subside at different rates, in different styles, at different times. Two main phases of rifting are recognised, Permo-Triassic, and Middle and Upper Jurassic. These two phases have contrasting patterns of subsidence, and contrasting structural expression, particularly as regards the extent of the involvement of the transverse fault zones. The Permo-Triassic phase is characterised by parallelism of stratal configurations, and horizontal subsidence of the graben floor, whereas the Jurassic phase is characterised by strongly divergent configurations and asymmetric, rotational subsidence directed towards and controlled by the Coffee Soil Fault. Active rifting ceased at the end of the Jurassic, and Lower Cretaceous sediments are found to onlap extant fault scarps in a passive infill of the rift basin.

The major bounding structures of the rift change strike abruptly in several incremental steps across the points of intersection with the transverse segment boundaries. The re-orientation of the rift is therefore explained as a consequence of the underlying presence of the earlier transform dominated basement fabric. A model for the formation of the North Sea Rift is proposed, which draws heavily on observations of the fracture patterns in continental rifts such as the Oslo Rift and the Rio Grande Rift, and is a development of the Megashear-Rhombochasm concept of S.W.Carey.

EXTENDED ABSTRACT

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Thesis submitted for the degree of Doctor of Philosophy, Hilary,1988.

A Seismic Interpretation of the Danish North Sea.

The major tectonic elements of the Danish Sector of the North Sea are the Danish Central Graben, the Ringkobing-Fyn High, the Horn Graben, the Else Graben, and the Northern Permian Basin.

The Ringkobing-Fyn High forms part of an E-W trending series of positive fault bounded blocks that were uplifted during the Late Carboniferous to Early Permian, during a phase of transtensional reactivation of a suite of NW trending fundamental continental lineaments in N.W.Europe. It is bounded on its southern and northern margins by WNW trending fracture zones, the Romo Fracture Zone, and the Vinding Fracture Zone. These fracture zones are narrow, linear zones of intense faulting at pre-Upper Permian structural levels, that can be traced from the east of Jutland into the North Sea. They probably developed as subsidiary splay shears to the Tornquist Zone.

The Ringkobing-Fyn High is transected at intervals by several N-S trending grabens. These are all segmented in form, and the positions of strike re-adjustment that mark the boundaries between adjacent segments are found to occur at the intersections with the WNW trending fracture zones. The initial opening of the Danish Central Graben, the Else Graben and the Horn Graben was coeval with the uplift of the Ringkobing-Fyn High, the intense faulting of the fracture zones bounding the high, and a phase of massive extrusive magmatism in N.W.Europe. The preferential location of the Late Carboniferous rifts at the terminations or offsets of elements of the network of NW trending lineaments supports the early interpretation of a strike-slip/pull apart mechanism for the early initiation and propagation of the rifts (Arthaud and Matté,1977).

The main emphasis of the seismic interpretation was placed on mapping the Danish Central Graben (DCG). The density of seismic and well data is much higher in the graben than over areas further to the east. A major objective of the study was to ascertain the nature of any structural controls on the adoption of a zig-zag trajectory by the North Sea Rift. The rift changes from a NW-SE trend in the Norwegian Sector to N-S trend in the Dutch Sector.

Detailed mapping of the DCG shows that the area of re-orientation is dominated by a WNW trending structural grain. The major boundary fault of the Tail End Graben changes strike abruptly at several positions along its length, and these positions are found to coincide with the points of intersection of several WNW trending transverse fault zones. Mapping of the transverse fault zones eastward into the rift shoulders is hampered by the coarse grid spacing, and it is not known whether they continue directly as basement fracture zones on the Ringkobing-Fyn High. However, the lineament-rift intersections mapped in the Horn and Else Grabens point to a similar relationship in the Tail End Graben, and it is significant that the projected continuations of the Romo and Vinding Fracture Zones would intersect the Tail End Graben at the points of strike re-arrangement. It is suggested, therefore, that the adoption of the zig-zag course by the North Sea Rift in the Danish Sector resulted from the wrench reactivation of the pre-existing basement fabric. The rift-rift offset pattern exhibited by the North Sea Rift can be viewed as the linking of two pull-apart rift elements along a reactivated transform zone.

The rhombohedral mosaic of fault bounded basement blocks that resulted from this arrangement of intersecting fault trends exerted a profound influence on the patterns of subsidence and sediment accumulation in the DCG. This influence was relatively subtle in the early stages of rift development during the Permian and Triassic, but became progressively more important as the style of fault controlled subsidence developed into a faster and more asymmetric form during the Middle and Upper Jurassic. The acceleration in the rate of extension in this second phase of rift development led to the exacerbation of the mosaic basement framework, and to considerable differential subsidence between adjoining blocks. The faulted boundaries of the blocks were either reactivated in a torsional sense or as simple fulcral hinges, depending on their orientation relative to the rift bounding structures, and their position along the rift relative to the main corridor of re-orientation. The block-basin framework is evident both from isochore mapping and from seismic facies mapping. In the economically important Upper Jurassic sequence, the reservoir prone areas are confined to the relatively elevated blocks such as the Dogger Platform. The structural hinges along the margins of the more rapidly subsiding central segments of the Tail End Graben were the loci for the development of shelf edges. Basinward of these hinged margins, the seismic facies are uniform and continuous, signifying low-energy slope drape or base of slope deposition. Mounded and lobate depositional forms are observed along the scarp of the Coffee Soil Fault, the major bounding structure of the Tail End Graben, and these are interpreted as submarine fans or fan deltas. Significantly, these Late Jurassic fans are only observed at positions along the fault scarp where the WNW trending transverse segment boundaries intersect the fault plane. This observation of a structural control on the location of scarp-related fan deposits may have a predictive value in the exploration for reservoir bodies in rift settings.

The contrast between the two main phases of rifting is clearly seen from the difference in the gross reflection configurations of the Permo-Triassic and the Middle and Upper Jurassic. The former are parallel and continuous, whereas the latter are strongly divergent. The contrast is an expression of the change from horizontal to rotational modes of subsidence, from symmetric to asymmetric forms of extension. This change in regime is explained by reference to the inherent mechanical anisotropy of the crust, and the differing influence this exerts under varying conditions of strain rate and heat flow.

Active rifting ceased in the Late Jurassic. Thereafter, the deep marine basin was progressively infilled by onlapping Lower Cretaceous shales. Onlap geometries on remnant fault scarps indicate that water depths may have been of the order of 600 metres at the beginning of the Cretaceous.

A comparison of fracture patterns in a variety of rifts shows that segmentation is a common attribute of the morphology of continental rifts. The Oslo Rift and the Rio Grande Rift are particularly well documented examples of segmented rifts, which, in addition, exhibit diachroneity of opening. The propagation of these two rifts seems to have occurred in a step-wise fashion, in which the jumps in propagation can be seen to have taken place at points of intersection with major, transversely oriented continental lineaments. The continental lineaments also form the principal loci for extrusive magmatism associated with the formation of the rifts. By analogy with the phenomenon of crack blunting in fracture mechanics, it is proposed that the segmentation is an expression of a sporadic fracture propagation which is conditioned by the buttressing effect of deep seated pre-existing fractures oriented at high angle to the direction of propagation. Reference is made to the original concept of wrench-induced rifting proposed by S.W.Carey, in formulating a general explanation for segmentation in continental rifts.

The documentation here, of the durability of major continental lineaments such as the Tornquist Zone through several phases of ocean formation and closure, raises a number of questions of relevance to wider issues of global tectonics. The arguments presented in favour of a tearing mechanism for the formation of rifts require that there be a motive element capable of providing the necessary torsion. It is speculated that the Earth's rotation may have a significant influence on the pattern of global tectonics, particularly during periods of abnormal heat production, conduction and convection.

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The germ for this project was planted during my residence at S.I.P.M, the Hague, and I would like to express my gratitude to several people who guided me through the early lessons of seismic interpretation and hydrocarbon exploration, Carel Louwerens, Dan Griffin, Peter Ziegler, and Willy van Tellingen.

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I am indebted to Merlin Geophysical Ltd., for providing access to a magnificent collection of seismic lines, and to Dr. T. Kilenyi for numerous discussions and for logistical support.

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CHAPTER ONE: INTRODUCTION.

1.1 HISTORICAL PERSPECTIVE OF RESEARCH ON CONTINENTAL RIFTS.

Research on continental rifts dates back to the turn of the 19th century to the pioneering work of Gregory(1896), who first introduced the concept of a tensional origin for the rift valleys of East Africa. The first alternative hypothesis for the origin of continental rifts was proposed by Wayland(1921). Whilst mapping the region surrounding Lake Albert, he noticed that the fault scarps bordering the rift were staggered or offset at seemingly regular intervals and at complimentary positions on either side of the lake. The offset portions of the scarps were often sites of oil seeps and hot springs, and this observation led him to suspect a deep-seated origin for the fractures underlying the rift. He recorded a number of instances of horizontal striae on slickenside surfaces along the offset scarps, and correctly interpreted these as indicating a component of shear on the fractures. Wayland drew on these observations to propose that the Lake Albert Rift was transected by a number of transverse shear faults arranged in such a way as to give the impression of a rhombohedral network of fault bounded blocks. Unfortunately, he took this perceptive observation to indicate that the transverse shear faults formed in an analogous fashion to shear planes under quadrilateral compression. This conclusion then formed the basis of his compression theory for rifting which received little public support.

The observations made by Wayland were lost to a more general audience as a direct result of their being associated with an unpopular idea. As is often the case, however, the observational side of good

science inevitably proves to be more durable than the analytical, and now, more than sixty years after the publication of Wayland's original and perceptive observations on the fracture pattern in a continental rift, his contribution can be judged in the context of more sophisticated techniques at the disposal of modern investigators of rifts.

In the post-war years, the development of geophysical techniques such as refraction seismic and gravity surveying had a profound influence on ideas concerning the formation of rifts. Rifts were found to be associated with large positive gravity anomalies, and refraction seismic imaging of the deep structure of rifts led to the realisation that the Mohorovicic Discontinuity was at much shallower depths under the axis of the rifts than under their shoulders. These observations led, in turn, to the hypothesis that rifting was an active process related to the intrusion of mantle plumes. This idea was attractive because of its relevance to mantle convection hypotheses, and because it appeared to satisfy the observed relationship of crustal doming, prolific extrusive magmatism and continental fragmentation. Triple-armed rift juctions were recognised in the Rhine Rift, the East African Rift and the North Sea Rift, and were regarded as the consequence of plume-induced crustal doming.

In the late 1970's, as a result of advances in structural geology and seismology in areas of active rifting like the Aegean, a new approach began to dominate thinking on rift formation. Lithospheric stretching (McKenzie,1978) was an essentially passive view of rifting that sought to explain the development of sedimentary basins as a two-stage process, commencing with a rapid rift phase, followed by a

longer phase of regional basin development arising from the cooling of a rift-induced thermal anomaly.

The introduction of this concept coincided with a resurgence of interest in extensional tectonics, inspired principally by field based studies of the Basin and Range province of the western United States. A growing body of opinion became established in favour of listric geometries for major extensional faults, and rift and passive margin basins were found to conform in a general sense to the predictions of the stretching model.

In the ebb and flow from one fashionable standpoint to another, there comes a time when the weight of good observational science finally matches the rate at which variants of the dominant concept are spawned. The advances in techniques of reflection seismic acquisition in the early 1980's now afford an opportunity to improve the balance of observation in the study of the origins of continental rifts, and it is to this goal that this thesis is directed.

1.2 AIMS AND SCOPE OF THE THESIS.

The central aim of this thesis is to present a detailed three-dimensional analysis of the structural and stratigraphic evolution of a rift basin based on a tight grid of reflection seismic data, and to provide a well constrained case study of an extensional province against which numerical and geometric models can in future be tested.

The Danish Sector of the North Sea Rift was chosen because a tight grid of modern, high resolution seismic data was available for academic research purposes (figure 1.2). The Danish Sector is of particular interest in that it encompasses an area where the variably oriented U.K/Norwegian Central Graben and the Dutch Central Graben intersect (figure 1.1). It was considered that mapping and analysis of the

intersection zone might provide some explanation for the zig-zag course adopted by the rift. The other zone of intersection of the zig-zag is between the Central Graben and the Viking Graben at the Forties area (figure 1.1). This has been regarded as a plume induced triple junction on account of the occurrence of a Jurassic volcanic centre and the regional development of a major stratigraphic break in the Early Jurassic (Whiteman et al.,1975, Ziegler,P.A,1982). This view of the origin and significance of the Forties intersection has been questioned recently by Pegrum(1984a), who on the basis of structural mapping in the Norwegian Sector, has suggested that the Tornquist Zone extends across the North Sea to intersect the rift precisely at the junction of the Viking and Central Grabens, and the volcanic centre may instead be related to 'magmatic leaking' along this deep seated continental fracture zone. By studying the Danish intersection, it was hoped that these differences of opinion regarding the re-orientation of the rift farther north might be resolved. Furthermore, regional structural mapping of a reconnaissance seismic grid over areas to the east of the rift in the Danish North Sea, might also prove important in understanding the role of the Tornquist Zone in the formation of the various rift basins of the N.W.European platform.

Many continental rifts appear to be sub-divided into segments (Cartwright,1988b), which often have markedly varying structural and stratigraphic characteristics. The North Sea Rift is an excellent example of a segmented rift, and there are significant differences in the structural evolution of the three main rift elements. The phenomenon of segmentation is poorly understood. A final objective of this thesis, therefore, is to investigate the significance of segmentation, using the

Danish Sector as a base for a comparison of the structural morphology of a number of other rifts.

1.3 REGIONAL GEOLOGICAL SETTING.

The Danish Sector of the North Sea encompasses several major tectonic elements (figure 1.1), the Danish Central Graben (DCG), the NE flank of the Mid North Sea High (MNSH), the Ringkobing-Fyn High (RFH), the southern margin of the Northern Permian Basin, and the Horn Graben. Hydrocarbon exploration has been confined to the DCG and its immediate flanking shoulders, but the piecemeal manner in which seismic and well data have been made available for study has resulted in a confused structural nomenclature. The nomenclature used herein follows, where appropriate, preceding definitions, but differences in the structural interpretation of this thesis have necessitated a revision of some of the terms used in previous accounts.

The principal structural components of the DCG are illustrated in figure 1.3. The Feda and Tail End Grabens are, respectively, the continuation into the Danish Sector of the NW-SE trending U.K/Norwegian Central Graben and the N-S trending Dutch Central Graben (figure 1.1). The Feda Graben is fairly symmetric in cross-section. It is bounded by the Mandal Fault and the Lindesnaes Ridge, and bisected by the Gert Ridge. The Tail End Graben is strongly asymmetric with a half-graben form bounded to the east by the controlling Coffee Soil Fault. The Jens-Otto Fault Zone forms the western margin of the graben, and acted as a hinge for the rotational subsidence accompanying the large displacement on the Coffee Soil Fault. Both these margins are composed of a number of linear strands. At three positions along the length of the Tail End Graben, there are abrupt changes in the strike or offsets of the margin structures, and in each case, these are linked from margin

to margin by complex fault zones. These fault zones divide the Tail End Graben into four segments, hereafter referred to as the Sogne Basin (following Gowers and Saeboe,1985), the NTEG (Northern Tail End Graben), the CTEG (Central Tail End Graben), and the STEG(Southern Tail End Graben).

South-east of the Feda Graben and west of the Tail End Graben is a triangular shaped area termed here the Dogger Platform. This area has previously been referred to as the Dogger High (Michelsen, 1982), the Vigeland Ridge (Gowers and Saeboe, 1985), and the Inge High (Frandsen et al., 1987). It acted as a stable fault bounded block relative to the adjacent rapidly subsiding graben areas, but was never fully coupled to the positive areas on the rift shoulders. The Dogger Platform is separated from the more elevated Mid North Sea High and from the small half-graben Outer Rough Basin by the Olaf Fault Zone. This is a complex discontinuous WNW trending array of faults and folds and small-scale horst and graben structures. Two of the more prominent horsts are the Dogger High and the Mads High.

1.4 PREVIOUS RESEARCH ON THE DANISH CENTRAL GRABEN.

Most of the research carried out on the DCG has been stratigraphic. The results of drilling in the area prior to 1977 formed the basis for a synthesis of the structure and stratigraphy of the DCG published by the Danish Geological Survey (Michelsen,1982). Whilst representing the first attempt at defining a stratigraphy for the DCG, the limited availability of high resolution seismic data at the time imposed severe constraints on interpretation of the stucture. Following the release of the regional seismic surveys acquired in the early 1980's, several publications have sought to re-assess the litho-stratigraphy by applying seismic stratigraphic techniques (Vejbaek,1986; Frandsen et al.,1987).

Gowers and Saeboe(1985), presented an interpretation of the structural evolution of the Danish and Norwegian Sectors based on a series of schematic isopach maps covering the Mesozoic era. Their emphasis lay on nomenclature rather than on detailed structural analysis, and they failed to include any seismic evidence in support of their account. Frandsen et al.(1987), and Vejbaek (1986), addressed the later (Jurassic and Cretaceous) phases of the evolution of the DCG, but made no attempt to consider the the regional implcations of their results. Cartwright (1987, 1988a,b, see Appendix B), has presented the results of a seismic interpretation of the DCG, and has discussed wider topics of rift development such as the significance of transverse structures in rifts, and basin inversion, using the DCG as an example.

1.5 GEOPHYSICAL DATA.

1.5.1 Seismic Data: Acquisition, Processing and Quality.

Approximately 10,000 kilometres of high resolution seismic data were used in this interpretation (figure 1.2). This comprised a large proportion of two regional surveys acquired in 1982, prior to the first licensing round, by Merlin Geophysical (SP survey) and Western Geophysical (DCS survey). Additional infill lines were selected from the North Sea regional well-tie survey acquired by GECO Ltd.

The combination of these various surveys gave a working grid of approximately 3 by 3 kilometres in the northern part of the DCG, 5 by 5 kilometres in the southern DCG, and 10 by 10 kilometres over the Ringkobing-Fyn High and Horn Graben. The SP and DCS surveys were oriented orthogonally to the main structural grain.

The SP and the DCS surveys achieved the highest standards of acquisition and processing. Large volume air guns ensured maximum

penetration of energy, the shooting interval was closely spaced (25m), and the towing depth was set to minimise shot-generated noise. In both surveys, cable length was 2950m, and the sections were recorded to seven seconds. The processing was a standard sequence for large regional surveys of this type. There are differences in the type of deconvolution operators, gain windows and frequency filters between the SP and the DCS surveys, and consequently the record sections differ considerably in character. The amplitude content of the Upper Cretaceous sequence is, for example, far higher in the SP data than in the DCS data. Resolution of intra-crystalline basement reflectors is greater in the DCS survey than in the SP survey. The acquisition parameters of both surveys were tuned for optimum resolution of the pre-Cretaceous exploration objectives, and this led to significantly deeper imaging of the structure than had been achieved in previous surveys.

From the point of structural clarity, the wave equation migration of the SP survey proved to be more effective than the finite difference method used for the DCS survey.

1.5.2 Potential Field Data.

Seasat and shipborne gravity data were interpreted using the shallow crustal structural interpretation from this study(Holliger, 1987). The results of the gravity modelling are presented in Chapter Five. Regional compilations of gravity and aeromagnetic data provided by Petrofina were used to define major tectonic features in areas with only a limited seismic coverage and also to constrain long wavelength, deep structure of the Ringkobing-Fyn High and the DCG.

1.6 WELL DATA.

The following wells were used in this project:-

Danish Sector: A-2, C-1, D-1, E-1, F-1, H-1, I-1, J-1, K-1, L-1, M-8, N-1, O-1, P-1, Q-1, U-1, R-1, S-1, T-1, U-1, W-1, V-1, Lulu-1, Adda-1, Per-1.

Norwegian Sector: 2/11-01, 2/10-01, 2/8-03, 2/9-02, 3/5-01, 3/5-02, 3/7-03.

U.K Sector: 39/2-01.

The Danish Sector wells were released under a five-year confidentiality agreement. The remaining data were obtained through Petrofina, U.K. Ltd. The information pertaining to each well was limited to completion logs, operator's lithological and bio-stratigraphic evaluations, and well-shoot and sonic derived velocity data.

1.7 CALIBRATION OF THE SEISMIC DATA AND CHOICE OF HORIZONS.

Three sources of stratigraphic information were used to calibrate the seismic data:-

(1) A report on the Stratigraphy of the Danish Sector, published by Robertson's Research Ltd., of Llandudno.

(2) Operator's formation tops.

(3) Well data summary sheets published by the Danish Geological Survey(D.G.U.).

Trial correlations performed in the undeformed central and southern segments of the Tail End Graben, established that the Robertson's picks yielded loop-ties within an acceptable range of 100 milliseconds, and as a result if there were substantial differences between the three reference sources for any given datum, the Robertson's picks were preferred.

Formation tops were converted to travel time using the results of well velocity surveys (well shoots). Synthetic seismograms proved to be of little practical value, in most cases because the seismic data do not

directly intersect the well trace, and jump correlations were required in order to obtain a good fit. The most continuous reflection events closest to principal stratigraphic boundaries identified in the wells were chosen for regional correlation. In every case these proved to be regionally significant unconformities or sequence boundaries (Vail et al.,1977). They were easily correlatable, often over large areas, and were defined in areas of only limited well control on the basis of downlapping, onlapping or toplapping reflection terminations.

Six major sequence boundaries were recognised and mapped over the Tail End Graben and all or part of the surrounding regions.

(1) Base Zechstein.

This is recognisable as a prominent high amplitude reflection throughout the Feda and Tail End Grabens. In areas where the sequence boundary cannot be identified purely from character, it can generally be recognised by its relationship with the overlying mobile Zechstein evaporite sequences. It is only calibrated by wells drilled on the Ringkobing-Fyn High (D-1, L-1).

(2) Base Middle Jurassic.

The precise stratigraphic significance of this sequence boundary is not yet known, as it is only penetrated by five wells, and these are all located in the Southern Tail End Graben. This limited control points to a diachronous hiatus ranging from the Late Triassic to the Callovian (Chapter 2.6).There is , however, no evidence for any major erosional event in the main graben areas, and it seems probable that the sequence boundary represents some form of relative still-stand, whose duration was controlled by local tectonic factors. The strong reflection which characterises this boundary over a large part of the area may be related to the presence of a thin sandy interval in the lower part of the Middle

Jurassic sequence, or may be related to the impedance contrast between shaly Jurassic rocks and the evaporitic or carbonate-rich uppermost Triassic sequence.

(3) Base Volgian.

This sequence boundary was calibrated in a number of wells located in the central and southern Tail End Graben. Seismic correlation between these wells resulted in a mistie of some 150 milliseconds two-way time (approximately 200 metres). In the absence of any intervening faults which might have caused problems in correlation of the reflection event, it seems probable that this error lies in the resolution of the biostratigraphic method of age determination from borehole source material. Nevertheless, it was possible to correlate the sequence boundary throughout the Tail End Graben. Intense deformation and lateral changes in the reflection character and thickness of the Upper Jurassic at the boundaries of the Dogger Platform and the Sogne Basin, prevented any direct seismic correlation from the main cluster of well control points. As such, the definition of sequence boudaries in these tectonically isolated areas was based entirely on wells drilled within a specific correlation 'province'. In the Feda Graben, the identification of a prominent onlap and truncation surface as the Base Volgian, was based on a long-range correlation to 2/11-01, drilled in the same fault-bounded block along strike in the Norwegian Sector. Two sequence boundaries were recognised on the Dogger Platform, but W-1 and Q-1 were both of limited value as calibration wells for the Jurassic sequence. These sequence boundaries are therefore only tentatively identified as Oxfordian/Kimmeridgian and early Volgian.

(4) Base Cretaceous.

This is characterised in the basinal areas by a high amplitude reflection. It is often associated with a pronounced basal onlap, but is only expressed as a truncation surface on the major structural highs. On the Dogger Platform and over the crests of salt structures, the Lower Cretaceous thins beneath the limits of seismic resolution, and the Base Cretaceous and Base Upper Cretaceous sequence boundaries cannot be distinguished.

There is considerable debate over the biostratigraphic and structural significance of this sequence boundary (Birkelund et al.,1983; Rawson and Riley,1982; and Chapter 2.7,this volume). The only likely source of the extremely high amplitude reflection which forms the sequence boundary is at the boundary between the 'hot shales' of the Kimmeridge Clay Formation (J-4 unit of Koch et al.,1982) and the more open marine shales of the overlying Valhall Formation. Sonic logs presented by Birkelund et al.,(1983) show an abrupt decrease in velocity at the formation boundary.

(5) Base Upper Cretaceous.

There is abundant well control for the calibration and correlation of this sequence boundary. The biostratigraphic resolution for the Cretaceous stage boundaries is much higher than for the Jurassic, and all three sources of stratigraphic information were in close agreement as to the position of the sequence boundary in the control wells.

The sequence boundary is easily recognised over structural highs (Dogger Platform, Mandal High) where there is evidence of considerable non-depositional hiati. In the Sogne Basin, for example, chalks of Santonian age lie without noticeable angular discordance on marls and shales of Aptian and Albian age. In the basinal areas, however, the

sequence boundary is less well defined. Over large areas of the Tail End Graben, for example, the boundary is characterised by several closely spaced high amplitude reflections (see Enclosures 13, 14 and 15), and correlation even over short distances between wells in the CTEG proved difficult. The continuity of deposition gave rise to a gradational lithological boundary, and with no clearly defined break in the acoustic impedance coinciding with the biostratigraphic boundary between Lower and Upper Cretaceous, no sharply defined reflection is produced.

(6) Base Tertiary.

This was chosen in preference to the more pronounced lithological break at the top of the Danian Chalk by virtue of greater reflection continuity. The Danian onlaps the Maastrichtian over axes of structural inversion, whereas the Maastrichtian is present in all but a few of the most intensely deformed areas. It is generally a high amplitude, high frequency, negative reflection, but in the axis of the CTEG, the upper chalks are developed in a discontinuous seismic facies, and the Base Tertiary event loses its continuity and becomes difficult to correlate. Occasional mis-ties between the seismic and well data may either be due to the correlation problem in the basin axis, or to errors in the biostratigraphic determinations caused by duplication of upper chalk intervals by slumping associated with structural inversion (Watts et al.,1980, Cartwright,1988a).

1.8 STRUCTURAL AND ISOCHORE MAPPING AND DEPTH CONVERSION.

1.8.1 Scale.

Mapping scales were chosen for each horizon on the basis of the line spacing of the seismic data, the intensity of faulting (magnitude of displacement and horizontal spacing of faults), the rate of change of

structural gradient, and the level of detail required for structural analysis or definition of hydrocarbon traps.

1.8.2 Structural Correlation.

The major structural elements of the DCG are widely spaced, and so the line spacing of 3-5 kilometres was sufficient to avoid aliasing during structural mapping. Along some of the complex faulted margins of the major elements, such as the Jens-Otto Fault Zone and the Olaf Fault Zone, the fault spacing is much less than the dip line spacing, and a degree of aliasing is inevitable (figure 1.4). Strike-parallel seismic lines were used extensively to attempt to overcome this problem (figure 1.5), but the mapped fault configurations nevertheless embody a significant element of subjective judgement. Specific problems of structural correlation are addressed in Chapter 3.

Strike lines were also important in defining the structural geometry of transverse fault zones in the Tail End Graben (figure 1.5). By virtue of their oblique orientation with respect to the rift margins, the transverse fault zones are difficult to recognise on dip lines, either because of poor migration of the oblique images or because of interference of off-line events. The example in figure 1.6 illustrates the kind of structural correlation that might be made if only dip lines are available, and if there are no diagnostic feature which indicates the presence of transverse structures. The addition of a strike line, and the correlation of the dip line border fault intersections with the strike line, then allows the interference effects on the strike line to be identified and mentally filtered. The disruption of events can be recognised as a structural feature as opposed to an artefact, and the interpretation can incorporate the anomalous fault zone and the border fault offset into a second structural correlation.

High angle intersections of individual faults or fault zones represent the most difficult problems in seismic interpretation. If a 3-D survey is not available, then a unique solution is unlikely to be obtained, and the structural correlation must rest mainly on the circumstantial evidence of relative timing of fault displacements. It is extremely rare to find unequivocal evidence of a fault offset relationship on a single seismic line.

1.8.3. Isochore Mapping.

Isochore maps were compiled manually. Computer based methods involving layer subtraction techniques are only appropriate in areas where the structural relief and faulting are minimal.

Time thicknesses of individual sequences were measured as close to normal to the bedding as possible, and were plotted vertically beneath the intercept with the lower sequence boundary (figure 1.7).

1.8.4 Depth Conversion.

Perhaps the greatest limitation in the use of reflection seismic data in structural analysis is the dependence of the method on an accurate knowledge of the velocity field at depth. Precise constraints of the velocity distribution are available only from borehole derived information either in sonic logs or well velocity surveys. Velocity models derived from stacking are less reliable, particularly at depth. Stacking is frequency dependent, and as a general rule-of-thumb, at two-way times greater than three seconds, or when the frequency content of the signal is less than about fifty hertz, the data can be stacked over a range of velocities 10-15% above and below the true formation velocity.

Well shoot and sonic-derived interval velocities from some twenty wells were used to compile plots of burial depth versus velocity for the

Triassic, Middle Jurassic, Upper Jurassic, Lower Cretaceous, Upper Cretaceous and Tertiary intervals. The plots showed a considerable spread in the interval velocities for any given stratigraphic interval, and these differences are attributed to structural inversion, undercompaction, lateral variation in lithology, or hydrocarbon saturation. There were insufficient penetrations of the pre-Cretaceous sequences to produce any reliable velocity/depth curves, and the control points were too erratically and sparsely located to be of any use in constructing velocity maps for the various intervals covered by the isochore maps. In view of these limitations, averaged values of interval velocities were used in depth conversion of the seismic data presented in Enclosure 22. These are as follows:-

Tertiary.....2000m/s.

Upper Cretaceous...4000m/s.

Lower Cretaceous...2,700m/s.

Volgian.....2,800m/s.

Oxfordian/Kimm.....3,000m/s.

Middle Jurassic....3,200m/s.

Triassic.....3,500m/s.

Upper Palaeozoic...4,500m/s.

CHAPTER TWO STRATIGRAPHY

2.1 INTRODUCTION.

Most of the research that has been carried out on the Danish Central Graben has been of a stratigraphic nature, and based in a large part on the results of exploration drilling. The most important synthesis of the petrophysical, bio-stratigraphic and litho-stratigraphic data arising from drilling is that of Michelsen (1982). This work was based on wells drilled up to 1977, and represented the first attempt to formalise the stratigraphy and integrate the findings in the Danish Sector with those elsewhere in the Central North Sea. At that time, there was only a limited amount of seismic data open for public inspection, and as such, this early stratigraphy was erected without seismic-stratigraphic constraints. There have been several recent modifications of the stratigraphic framework set up by Michelsen and his co-workers, following the release of additional well and seismic data, and as a result of more detailed bio-stratigraphic analyses (Birkelund et al.,1983). Frandsen et al.(1987) described the Jurassic and Early Cretaceous stratigraphy of the Danish Central Graben, and presented a review of the stratigraphic nomenclature (figure 2.34). Vejbaek(1986) made the first rigorous integration of the seismic data with the petrophysical results from the released wells, but limited the application of this seismic-stratigraphic analysis to the Lower Cretaceous. Gowers and Saeboe(1985) made use of seismic data in a structural analysis of the Danish and Norwegian Sectors of the Central Graben, but did not attempt a rigorous seismic-stratigraphic interpretation.

The aim of this chapter is to integrate the published stratigaphic data from all the available wells into a full seismic-stratigraphic interpretation of the Late Palaeozoic and Mesozoic sequences. The seismic stratigraphy of the Upper Cretaceous has been described in detail elsewhere (Cartwright, 1988a, see Appendix B).

2.2 CRYSTALLINE BASEMENT ROCKS.

Reviews of the nature of the crystalline basement of the Central North Sea are provided by Frost et al.(1981), and Ziegler(1982). These publications are based on only a small number of widely dispersed wells that have penetrated and cored crystalline basement. In the Danish Sector, only Per-1 and P-1 encountered basement (figure 2.1). Isotopic age determinations suggest Caledonian affinities for both wells. Caledonian ages were also obtained from medium to high grade gneisses in nearby German wells B/4-1 and Q-1, and Norwegian well 3/7-1 (Ziegler, 1982). Frost et al.(1981) made a petrographic and chronological analysis of all the available basement penetrations, and concurred with the earlier interpretation made by Ziegler(1978), of the existence of a mid-European branch of the Caledonides extending in an arcuate belt from the southern Norwegian Sector, along the Danish-German border to Poland (figure 2.2). This arcuate province boundary supposedly crosses the Ringkobing-Fyn High, but reconnaisance structural interpretation of this area (Chapter 4), indicates that an alternative interpretation is necessary. The regional geological implications of the basement structure of the Ringkobing-Fyn High are discussed in Chapters 4 and 5.

2.3 UPPER PALAEOZOIC ROCKS.

The stratigraphy and distribution of the Upper Palaeozoic in the Central North Sea is poorly understood (Glennie,1986). The sequence is penetrated in only a few wells, and many of these are located on Mesozoic structural highs where post-Palaeozoic deformation and erosion minimises their value for stratigraphic calibration of the seismic data. Published pre-Permian subcrop maps (Ziegler,1982, Glennie,1986) show a northern limit for the present day distribution of the Carboniferous along the axis of the E-W trending Mid North Sea and Ringkobing-Fyn High system. This is depicted on these maps as a truncation edge resulting from Late Carboniferous-Late Cretaceous uplift and erosion of the structural highs (figure 2.2). Neither the original depositional extent of the Upper Palaeozoic nor the nature of the basin subsidence mechanism are fully understood at present, and the origin of the central highs has only been briefly considered (Donato et al.,1983; Dewey,1982).

The Late Palaeozoic evolution of the Central North Sea is one of the major outstanding problems in the regional geological evolution of N.W.Europe. It is particularly important from the point of both understanding the factors influencing basin development in the Mesozoic, and the later stages of the Caledonian Orogeny. The Danish Sector holds the key to a clearer understanding of this region, but prior to the availability of regional high resolution seismic surveys over the area, there was little concrete data on which to base a regional structural and stratigraphic evaluation. This problem was compounded by the unprospective nature of the pre-Jurassic sequences, and the consequent lack of deep well penetrations, particularly on the Ringkobing-Fyn High.

The following section describes the Upper Palaeozoic of the Danish Central Graben. The Upper Palaeozoic of the Ringkobing-Fyn High is described in Chapter 4.

The Upper Palaeozoic is best resolved on the seismic data where the Mesozoic cover is relatively thin (figure 2.3). The sequence is highly reflective, particularly in the uppermost intervals, and the resolution is often good enough to support a seismic-stratigraphic analysis. This approach is further necessitated by the paucity of well penetrations of the Upper Palaeozoic in the Danish Sector and immediately surrounding areas (figure 2.3).

2.3.1. Mid North Sea High-Outer Rough Basin.

A thick Upper Palaeozoic sequence is preserved to the south-west of the Olaf Fault (figure 1.3). The sequence is part of a continuous, platform-type succession that extends over much of the Mid North Sea High. The sequence comprises approximately 4000-5000 metres of largely parallel bedded reflections, bound at its base by a prominent high amplitude event that can be correlated throughout the area in spite of its great depth of burial (figure 2.4). This deep event is the effective acoustic basement, but in the absence of any deep wells it is not known whether or not this coincides with the top of the crystalline basement. There is an indication of a basal onlap on to the event in some areas (figures 2.4, and 2.5) which favours the interpretation of the event as the basement/cover interface. Devonian sandstones rest directly on crystalline basement in B/4-1, but seismic data over this well were not available for comparison with the Danish data. Nevertheless, the results of this well strengthen the possiblity that the deep event emanates from a major Devonian basal unconformity. Two other possible interpretations are that the event emanates from either the top of the Middle Devonian limestone or the top of the Carboniferous Limestone. Both limestone

sequences are known from wells in the Central and Southern North Sea, and are recognised on seismic data as high amplitude reflections.

The sequence has been divided into three units on grounds of their seismic expression. These units are bound by regionally correlative reflections. A type section for this sub-division is presented in figure 2.4. The lower two units are characterised by opaque seismic facies. Faint internal reflections define a parallel stratification. The upper unit is characterised by a highly discontinuous, high amplitude and high frequency seismic facies. Progradational reflection configurations are evident on several of the seismic lines (figure 2.5). The seismic facies and sigmoidal reflection configurations observed from the upper unit is typical of deltaic depositional systems (Vail et al.,1977). The transport direction derived from the geometry of the sigmoidal reflections is to the east. The gross form of the upper unit is also parallel bedded. This crude parallel stratification of all three units extends throughout the area, and the only thickness variations are all attributable to minor syn-depositional faults in the hanging wall of the Olaf Fault (Chapter 3.6). This continuity and parallelism of gross reflection character over such large distances (more than 80 kilometres) usually only results from epeirogenic horizontal subsidence on a large regional scale, as for example was the case for the platform Lower Palaeozoic sequences of the Russian Shield (Watson, 1976).

The only bio-stratigraphic control of the sequence comes from 2/10-1 (figure 2.6). This well penetrated 160 metres of mixed clastics with minor intercalations of limestone and basalts dated as Late Tournaisian to Early Visean. The succession penetrated in the well correlates with the opaque middle unit as defined above. There is some uncertainty in the seismic tie to the well as it requires a jump

correlation across a complexly faulted zone (figure 2.6). This jump correlation suggests that the deltaic upper unit is of Middle to Late Carboniferous age. Cyclic deltaic sequences of sands, shales and coals were drilled in A/6-1 and B/11-2 along strike in the German Sector, and were dated as Namurian, which is taken as supporting evidence for the jump correlation shown on figure 2.6, and the stratigraphic interpretation presented in figure 2.7. The possibility remains, however, that the progradational upper unit may represent a combined Namurian/Westphalian sequence, particularly in view of the fact that further south, the Westphalian is commonly developed in the same high frequency, discontinuous seismic facies characteristic of the upper unit.

North-east of the Olaf Fault Zone, on the Dogger Platform/Dogger High, there is no conclusive evidence of any significant thickness of Upper Palaeozoic sediments preserved beneath the thin Mesozoic cover. P-1 was drilled on the crest of the Dogger High, and penetrated a thin sequence of Carboniferous shales overlying metamorphic basement. This suggests that the Dogger High, and possibly much of the Dogger Platform were elevated above depositional base level for a large part of the Upper Palaeozoic, although it is also possible that there was originally a much thicker cover of Carboniferous and this was eroded during the Mesozoic. It is possible that a full Upper Palaeozoic sequence was deposited over the Dogger Platform, but the observed erosional level would require a cumulative post-Palaeozoic uplift of the Dogger High of over 4000 metres. Carboniferous growth is evident on small faults in the hanging wall of the Olaf Fault, and it is probable that these faults developed in response to syn-depositional activity on this large basement fault. It is suggested, therefore, that the Olaf Fault was

probably active as an intra-basinal structure during the Upper Palaeozoic, and separated an area of persistent horizontal subsidence from a relatively less subsiding block(figure 2.8).

2.3.2 Southern Tail End Graben.

The pre-Zechstein sequence is clearly resolved in the Southern Tail End Graben, in spite of the thick, overlying Zechstein evaporites, and the rapid lateral variation in the thickness of the Mesozoic sequences. Further to the North, in the central and northern segments of the Tail End Graben, the Base Zechstein plunges to near the bottom of the record section, and it is not known whether a comparable pre-Zechstein sequence is present in these areas.

The type section for the pre-Zechstein is line SP 42 (figure 2.9). The pre-Zechstein is composed of two sequences, which are separated by a major angular unconformity. The upper sequence is characterised by parallel to gently divergent reflection configurations and an overall high amplitude and high frequency acoustic response. The angular unconformity at the base displays onlap and truncation. A strong fault plane reflection (emanating from the Coffee Soil Fault) forms the eastern limit of the tilted lower sequence, which implies that the tilting and truncation of the parallel bedded lower sequence resulted from rotation and uplift of a fault block. This interpretation of the stratal and structural relationships on figure 2.9 is illustrated in figure 2.10. The conclusion is that motion on the Coffee Soil Fault commenced some time prior to the deposition of the upper, onlapping sequence.

Since there are no direct well calibrations of the type section or any neighbouring sections, the chronostratigraphy must be deduced from

the stratal relationships and from regional geological considerations. The upper sequence is concordant with the Base Zechstein event, which suggests that the upper sequence is in part of Early Permian age. The maximum thickness of the Lower Permian recorded in the Danish Sector is less than 1000 metres, and since the upper, onlapping pre-Zechstein sequence reaches a maximum thickness of over 4000 metres (Enclosure 22), it is probable that most of the upper sequence is Late Carboniferous in age. There is no evidence for any hiatus within the upper unit, and it must, therefore, represent a single genetically related sequence. The high frequency triplet reflections that occur as discontinuous patches in the deeper part of the upper unit are strongly reminiscent of the Westphalian coal measure sequences of the Southern North Sea, and it is suggested, therefore that the upper sequence ranges from the Westphalian to the Early Permian.

The tilted and truncated lower sequence is penetrated in B/11-2, B/10-1, and B/4-1, in the German Sector. The age of the sequences encountered in these wells ranges from Devonian to Namurian, and it is concluded, therefore that the parallel bedded lower sequence of the Southern Tail End Graben is equivalent to that described from the Mid North Sea High. The major unconformity is regarded as the major pre-rift unconformity, and probably dates from the late Namurian to early Westphalian.

2.4 PERMIAN.

Late Carboniferous to Early Permian vulcanism in the Southern North Sea, Denmark and Germany was followed by the establishment of two major Permian depocentres, the Northern and Southern Permian Basins (Ziegler,1982). Isopach maps for the Lower and Upper Permian show the outline of these two basins, and the extent of the intervening central high trend along the E-W Mid North Sea and Ringkobing-Fyn Highs (figures 2.11 and 5.27). On Ziegler's palaeogeographic reconstruction (figure 2.12), there is no indication of any active Permian rift along the lines of the Danish Central Graben, although it has been argued on detailed sedimentological grounds that the central highs must have been breached at least as early as the Thuringian transgression (Glennie,1986). The conclusion drawn from the stratal relationships of the Upper Palaeozoic of a Late Carboniferous inception of rifting in the Danish Central Graben suggests that the earliest rifting took place during a phase of massive flood vulcanism and uplift along the E-W trending Mid North Sea and Ringkobing-Fyn Highs (figures 2.3 and 5.28). The inter-relationships between the rifting, uplift and vulcanism are considered in Chapters 4 and 5.

2.4.1 Late Carboniferous-Early Permian Volcanic Rocks.

Extrusive volcanic rocks of Late Carboniferous or Early Permian age have been encountered in nearly all the wells drilled in the Danish Sector that penetrate the pre-Zechstein. Unfortunately, many of the wells reach T.D in the volcanic sequence, and this fact coupled with the sporadic distribution of the control wells prevents a detailed analysis of the original distribution and thickness of the sequence.

Radiometric age dates of the volcanic rocks presented by Jacobsen and Larsen(1982) show a large spread, from Cretaceous ages (W-1), to

Late Carboniferous (C-1). Dixon et al.(1981) reported extensive replacement of groundmass mineral phases in basalts used in the radiometric age studies by red, hydrated iron oxides and iddingsite, and suggested that this resulted from post-emplacement alteration in the arid climatic conditions. It seems probable, therefore, that the range in radiometric dates stems from analysis of diagenetically altered specimens, and does not provide any reliable constraint on the age of the igneous activity. The Stephanian/Autunian radiometric age for the C-1 well is consistent with the stratigraphy of the well. The ubiquitous intercalation of lava flows and volcanoclastic rocks with reddish-brown claystones, siltstones and sandstones in this and other wells is strong circumstantial evidence in favour of a Late Carboniferous-Early Permian age range for the volcanic phase.

The petrology and geochemistry of volcanic rocks cored in Central North Sea wells was studied by Dixon et al.(1981). They found that the lavas were bimodal, ranging from olivine tholeiites to quartz normative or potassium enriched types. The major element chemistry of these lavas was found to be similar to that exhibited by the flood lavas of the main igneous centres in Northern Germany and in the Oslo Rift. Dixon et al.(1981) regarded the bimodal suite as typical for an intra-plate rift setting, and drew a comparison with the Tertiary Colorado Plateau Volcanic Province of the western United States.

In the general area of the Danish Central Graben, the volcanic sequence is known from P-1, B-1, W-1, Q-1, D-1,L-1, A/6-1, 2/7-2, and 2/10-1 (figure 2.3), suggesting a fairly widespread occurrence. All these wells are located close to major faults which are known to have been active during the Upper Palaeozoic (see Chapter 4), and which may conceivably have acted as conduits for the extrusion of magma.

The seismic expression of the volcanic sequence is difficult to determine because of the limited vertical penetrations in the wells, and the seismic data can not be used to constrain the distribution. One example of a seismically defined volcanic sequence comes from a Late Carboniferous- Early Permian graben on the Ringkobing-Fyn High, immediately adjacent to the Southern Tail End Graben (see Chapter 4). The volcanic rocks are thought to be associated with a major unconformity forming the base of the graben-fill(figure 4.14), which is thought to be the equivalent pre-rift unconformity to that described previously from the Southern Tail End Graben. The unconformity surface corresponds to a highly irregular, high amplitude reflection with topographic relief of 50-100 metres, typical of erosion surfaces on volcanic terranes (Bally,1983).

2.4.2. The Upper Rotliegend.

The only conclusive penetration of the Upper Rotliegend in the Danish Central Graben is in the B-1 well, where a thin succession of reddish-brown silty sandstones and interbedded evaporites is found above the volcanic 'Lower Rotliegend'(Jacobsen and Larsen, 1982). Similar lithologies were encountered near T.D in W-1, Q-1, and P-1, but in the absence of relatively complete overlying Mesozoic sections with which to constrain the stratigraphy, it is not possible to differentiate Upper Rotliegend from either marginal facies Zechstein or Triassic. All these sequences are developed in similar lithofacies, biostratigraphic means for distinguishing between the possible alternatives are hampered by the paucity of fauna and flora. The wells are located on Mesozoic structural highs, where the condensed and attenuated sequences are often at the limit of vertical seismic resolution (e.g. Enclosure 13), and the seismic-well ties are inconclusive. In the basinal areas, however, where

the Upper Rotliegend is more fully developed and was free from later erosion, the sequence has a recognisable seismic expression (figure 2.13). This sequence is calibrated on the northern margin of the Ringkobing-Fyn High east of the truncated apex of the rift shoulder (figure 2.42), in D-1, and 3/5-1, where it is found to be composed of a mixed red bed clastic succession with minor intercalations of evaporites (Jacobsen and Larsen, 1982).

Upper Permian sediments probably form part of the upper pre-Zechstein sequence in the Southern Tail End Graben (section 2.3.2). A reflective pre-Zechstein sequence comparable in overall seismic expression to that observed in the Southern Tail End Graben, is also recognisable in the Sogne Basin (Enclosure 12, figure 2.25). It is probable, therefore, that this Westphalian-Lower Permian sequence extends along the full length of the Tail End Graben. The well and seismic data thus point to an established N-S graben transecting the E-W trending highs, and controlling the accumulation of the Upper Rotliegend (figure 2.14).

2.4.3. Upper Permian.

The notion of a fully established N-S trending rift breaching the Mid North Sea and Ringkobing-Fyn Highs during the Late Carboniferous and Permian is further strengthened by consideration of the Zechstein facies distribution in the Danish Sector. Figure 2.15 is a palaeogeographic reconstruction of the Upper Permian, based on the few available well penetrations of the Zechstein, and on a simple seismic facies analysis. Two seismic facies are recognised:-

(1)Basinal; opaque to low amplitude , configurations parallel or chaotic. This is believed to represent the basinal, evaporite dominated sequences of the Z1 to Z4 cycles (Taylor, 1981).

(2)Marginal; high amplitude, low frequent events with mounded/sigmoidal reflection configurations (see figure 2.17). This is believed to represent the carbonate/anhydrite dominated bank-lagoonal-reef sequences typical of the Z1 and Z2 cycles on the basin margins (Taylor, 1981). The juxtaposition of these two facies is clearly identifiable on seismic lines across the southern margin of the Northern Permian Basin (figure 2.16).

Reconstruction of the original depositional extent of the Zechstein is complicated by the widespread redistribution of the mobile evaporites during Jurassic and Cretaceous halokinesis (Gowers and Saeboe,1985: Michelsen and Andersen, 1983). In this respect, the accurate identification of the marginal facies is of paramount importance, since the carbonate/anhydrite sequences are immobile and therefore remained unaffected by later movements. The distribution of this facies thus provides a guide to the original position of the basin margin. Those areas with large numbers of closely spaced diapirs or pillows were almost certainly basinal, since the most mobile evaporite mineral is the basinal halite.

The marginal facies Zechstein is recognised as a discontinuous, mounded, high amplitude seismic facies. Z1 and Z2 reef or bank sequences with an identical seismic expression to those illustrated in figures 2.16 and 2.17 have been drilled along the northern margin of the Southern Permian Basin in South Jutland (D.G.U reports on Loegumkloster-1 and Brons-1). This northern margin of the Southern Permian Basin is structurally controlled. The margin coincides with a major shear zone that extends from Lolland and Falster in the East, to the Horn Graben offset zone in the West (figure 4.1). Similarly, the southern margin of the Northern Permian Basin along the boundary of the

Ringkobing-Fyn High is also closely related to major, deep seated faults (Chapter 4). The transition from marginal to basinal facies is beautifully preserved along this margin, and the original depositional relationships are completely unaffected by either tectonic or halokinetic activity (figure 2.16).

Considerable halokinesis is evident on the seismic data in the Sogne Basin, along the Jens-Otto Fault Zone flanking the Northern Tail End Graben (Chapter 3.2.5), in the Southern Tail End Graben, and from the Norwegian section of the Feda Graben (Gowers and Saeboe,1985). These areas are all shown in figure 2.15 as having been basinal during the deposition of the Zechstein. The largest volume of mobile evaporites occurs in the Southern Tail End Graben (the Southern Salt Dome Province of Michelsen, 1982). From a simple appraisal of the volume of mobile evaporites now represented by the halokinetic structures, it is evident that the Southern Tail End Graben must have been an area of pronounced subsidence during the Upper Permian.

The later halokinetic structures include several large pillows (figure 2.9 and Enclosure 18), several small, cylindrical piercement structures, and several large diapirs. These halokinetic structures occur above or close to faults affecting the Base Zechstein. It is probable that the mobilisation of the evaporites was triggered by later (i.e post Permian) seismic activity on the faults. It is also commonly observed that the faults in question do not always extend upwards into overlying Triassic and Jurassic sequences(e.g the Anne Pillow on figure 2.9). This is usually explained in terms of the ductile response of the evaporites under an applied stress. It is supposed that motion on the sub-Zechstein faults is relieved by ductile flow, and is therefore not transmitted into the cover (Glennie and Boegner,1981).

Close inspection of some of the pillow structures in the Southern Tail End Graben, however, draws attention to the possibility of considerable syn-depositional activity on intra-basinal faults, and raises a number of points concerning tectonic controls of the distribution of Zechstein facies.

On several of the intra-basinal faults with offsets of the Base Zechstein (Enclosure 1), there are marked differences in the seismic expression of the Zechstein on the upthrown and downthrown sides. On line SP-42 (figure 2.9), for example, allowing for the obvious flow of evaporites towards the large pillow structure, there is a clear increase in the thickness of mounded facies Zechstein across the fault. It is extremely improbable that marginal facies evaporites could have been mobilised, due to the complex stratification of dolomitic and anhydritic lithologies, and consequently, the increase in thickness across the fault is interpreted as evidence of syn-depositional faulting. Marginal facies Zechstein is observed in several positions in the basinal province of the Southern Tail End Graben, generally close to the uptilted margins of rhombohedral fault blocks (figure 2.15). This suggests that active faulting was not just confined to basin bounding faults such as the Coffee Soil Fault (figure 2.15), but was also taking place on linked networks of smaller intra-basinal faults. Small rotations of the fault blocks may have been expressed at the depositional surface in such a way as to promote reef and bank development on the shoaling, upthrown sides of the faults. In more marginal environments, the syn-depositional faulting only resulted in thickening in the same facies, or possibly in the development of scarp related talus slopes and bank edges (figure 2.18). This view of active fault control on the distribution of Zechstein lithofacies is based

solely on the relations observed between seismic facies and faults, and is not controlled by well data. Nevertheless, the Zechstein depositional model illustrated in figure 2.18, challenges the orthodox view of deposition on stably subsiding floors in the Permian Basins with regional uniformity of lithofacies, and raises the possibility of a system of small, fault controlled mini-basins with a localised, tectonically controlled arrangement of marginal and basinal facies types.

It is not known whether the Central Tail End Graben and Dogger Platform were sites of mainly marginal or basinal facies deposition. The Zechstein is buried beyond seismic resolution in the central segments of the Tail End Graben, and the wells drilled on the Dogger Platform are enigmatic from a lithostratigraphic point of view. B-1, D-1, and L-1 penetrated marginal facies Zechstein (figure 2.15), but thin sequences of red shales and evaporites encountered in W-1 and Q-1 could be Upper Rotliegend, marginal Zechstein, or Triassic. A pillow of Zechstein evaporites can be seen on seismic data over the Dogger Platform, preserved along with a thin sequence of Triassic from later erosion by a low-angle normal fault (figure 2.19). This isolated occurrence may possibly be the final remnant of an originally much more extensively distributed basinal facies, which may have linked the basinal areas in the Feda and the Southern Tail End Grabens across the Dogger Platform. Alternatively, the same fault which was ultimately responsible for the preservation of the pillow feature may have also controlled the original deposition, in the manner suggested above (figure 2.18), and pod of basinal Zechstein may have been a localised fault controlled basin set amongst a dominantly shallow and stable platform of marginal-type deposition. The preferred interpretation is illustrated in figure 2.15.

Whilst there was almost certainly a marine connection along the axis of the Tail End Graben, there was a medial zone of lesser subsidence and shallower water depths along the projection of the E-W trending central highs over the Dogger Platform. This reconstruction differs from that proposed by Gowers and Saeboe(1985), who regarded the distribution of the Zechstein along the Tail End Graben as a post-depositional phenomenon involving a Mid-Triassic to Mid-Jurassic phase of faulting and erosion.

2.5 TRIASSIC.

The evolution of sedimentary basins in N.W.Europe in the Triassic followed directly on from the patterns of regional subsidence established in the Late Carboniferous and Permian (Ziegler,1982). A broad zone of taphrogenesis developed along the Caledonian and Variscan orogenic belts as a precursor to full oceanic separation of the modern Atlantic later in the Mesozoic. In the North Sea region, this was expressed as a renewed phase of extensional faulting on many of the earlier formed fractures, and the consolidation of Late Carboniferous-Early Permian rift basins (figure 2.20).

The Central North Sea Highs were emergent or partially submerged throughout the Triassic. Major Triassic depocentres in the Southern North Sea are the Danish-Norwegian Basin, the Horn Graben, the Sole Pit Basin, and the Dutch-Danish Central Grabens. Reconstruction of the original depositional limits of the Triassic is plagued by the same difficulties described earlier for the preceding sequences; namely, absence through later uplift and erosion, scarcity of well control, and difficulty of lithostratigraphic correlation. However, the Triassic has a very characteristic seismic expression, and it is possible to identify

the sequence solely on character in deep areas of the graben where there is no well control.

2.5.1 Feda Graben.

There are no well penetrations of the Triassic in the Feda Graben, but a high amplitude, parallel bedded sequence is observed above the acoustic basement, and from comparison with similar sequences in the Southern Tail End Graben this is interpreted as Permo-Triassic (Enclosure 12). The sequence is bound at its base by a prominent high amplitude event, which from character and its relation with the overlying sequence is interpreted as the Base Zechstein. A representative section is shown with this interpretation in figure 2.21. A gently truncational upper boundary is interpreted as the Base Middle Jurassic on the basis of jump character correlations of the overlying sequence with the Haldager Formation (Middle Jurassic) of the Sogne Basin (c.f. figure 2.25).

The Triassic has a uniform thickness of c.1000 metres in the main part of the graben south-west of the Gert Ridge, but this original thickness was attenuated towards the Dogger Platform by erosion during the Middle-Late Jurassic. This phase of erosion was very pronounced north-east of the Gert Ridge, and the original extent of the Triassic across the Feda Graben is difficult to reconstruct. The fully preserved sequences in the adjacent fault blocks south-west of the Gert Ridge and east of the Mandal High are comparable in their thickness and in their parallel confurations, and it is likely that a single, horizontally subsiding graben floor linked these three areas during the Triassic. The occurrence of a thick Triassic sequence in the south-western block of the Feda Graben, and the absence of the Triassic through non-deposition on the adjacent Mid North Sea High implies that the WNW trending graben

bounding fault must have been active during the Triassic (see Chapter 3.21).

2.5.2 Dogger Platform.

Seismic and well data suggest that the Triassic is absent over large parts of the Dogger Platform (Enclosures 13 and 14).Jacobsen(1982) reported a Scythian age for a thin sequence of reddish-brown shales encountered beneath an extremely condensed section of Middle and Upper Jurassic shales and sands in Q-1, but the Triassic is entirely absent in both W-1 and P-1(Appendix A, figure 2.23). South-west of W-1, is a small downfaulted block, in which a partially eroded Permo-Triassic sequence is preserved (figure 2.19). The sequence is identified as Permo-Triassic from its high amplitude, parallel bedded seismic expression. The parallel configurations are suggestive of an originally much larger depositional extent over the Dogger Platform (figure 2.22), but later erosion removed all but a few isolated fault bounded remnants.

2.5.3 Tail End Graben.

A thick Triassic sequence occurs in all four segments of the Tail End Graben (Enclosure 6). Seismic resolution of this sequence is clearest in the Sogne Basin and the Southern Tail End Graben, where Jurassic subsidence was less pronounced, and travel times to the Base Zechstein are generally less than 5 seconds (Enclosure 1). Well control is restricted to the Southern Tail End Graben. Considerable thicknesses of Triassic were encountered in U-1, O-1, and M-8 (figure 2.23, and Jacobsen,1982). These three wells provide a limited calibration of the seismic data. U-1 was originally thought to penetrate virtually a complete section (Jacobsen,1982), but later analysis of dipmeter logs suggested a thrust repetition in the well (Michelsen and Andersen,1983),

which is confirmed by recent seismic data (figure 3.11). The lithostratigraphy of the drilled sequences has been described in detail by Berthelsen(1980), and Jacobsen(1982). These authors refer the sequence to a Central Graben Facies Province, which is comparable with the Triassic of the Southern North Sea as described by Rhys(1974)(figure 2.24).

The Triassic of the northern margin of the Ringkobing-Fyn High has a similar four-fold lithostratigraphic sub-division to that found in the Southern North Sea (figure 2.24). There is, however, an increase in the clastic content arising from the proximity to the source area of the Scandinavian shield, and this sequence is referred to the Germano-type Facies Province by Berthelsen(1980). The seismic expression of the Triassic in the Sogne Basin is comparable with that of the northern margin of the Ringkobing-Fyn High (c.f figures 2.25 and figure 2.26), so the Sogne Basin is regarded accordingly as part of the northern palaeogeographic province.

The Triassic of the Southern Tail End Graben is characterised by laterally continuous, high amplitude reflections, that emanate from several fairly thick carbonate and evaporite units in the Haisborough Group (figure 2.24). These continuous reflections can be correlated over a large area, and define a parallel bedded sequence geometry with only gradual lateral thickness variations (Enclosures 18 and 19). The thickness variations apparent in the isochore data (Enclosure 7), arise from slight truncation of the Triassic over halokinetic structures at the Base Middle Jurassic sequence boundary, and from thickening associated with evaporite withdrawal (figure 2.9).

The isochore map shows a consistent thickening towards the east, along the length of the Coffee Soil Fault. The maximum thickness of

c.2,500 metres is recorded in the Ryan detachment structure (Enclosure 22), but the structural complexity obscures the original stratal relationships. Strike seismic sections show a gradual northward thinning of the entire Triassic sequence towards the Central Tail End Graben, to an average lower value of 500-600 metres (Enclosures 18 and 19).

A pronounced eastward thickening of the Triassic is also observed in the Central and Northern Tail End Graben (Enclosures 7, 13, 14, and 15). The sequence is slightly truncated at the Base Middle Jurassic on the western margin of the graben(Enclosures 13,14 and 15). The thickening is confined to the upper part of the sequence, where the divergent reflection configurations indicate rotational subsidence of the major basement faults on the eastern margins. The seismic resolution of the Triassic in the Northern and Central Tail End Graben segments is poor owing to the large depth of burial under a very thick Jurassic cover. The loss of the higher frequencies makes direct comparisons of the seismic expression with the reference sections of the Sogne Basin and the Southern Tail End Graben unreliable, and it is not clear whether there is greater affinity of this central zone with the Germano-type or the Central Graben Facies Provinces. The thickness of the Triassic in this central part of the Tail End Graben is, however, considerably less than in the north and south, and it is probable that barriers to communication along the graben existed intermittently in this zone of more restricted subsidence. This may explain the contrast in lithofacies and seismic expression from one end of the graben to the other. The lesser subsidence of the two central segments may be an expression of the underlying E-W trending axis of relative uplift between the Mid North Sea and Ringkobing-Fyn Highs.

The interpretation of the original depositional limits of the Triassic, and the major controlling tectonic elements is summarised in figure 2.22. This interpretation differs from that proposed by Gowers and Saeboe(1985), who viewed the establishment of the Tail End Graben and the Dogger Platform-Vigeland Ridge as post-depositional(post Middle Triassic). These authors did not consider the stratigraphic relationships on the flanking highs, where the Triassic can be clearly seen to be absent through non-deposition, as opposed to later erosional truncation (figure 2.26). Syn-depositional activity on all the graben bounding faults must have been continuous throughout the period in order to explain the accumulation of the large thicknesses of mainly terrestrial Triassic sediments. The fault controlled subsidence varied from horizontal to rotational in the central segments of the Tail End Graben. It is difficult to explain the divergent Upper Triassic sequences in any other way than as syn-rotational deposits. It is concluded, therefore, that Triassic deposition in the Danish Central Graben was controlled throughout by WNW and NNW trending basement structures, that had served to localise deposition within the newly developing Late Carboniferous and Permian Rift.

2.6 JURASSIC.

The early formed structural elements continued to control the subsidence pattern and the organisation of the depositional systems during the Jurassic, but in addition, reactivation of the WNW trending basement grain led to an increase in the influence of faults that were transverse or highly oblique to the principal rift axes. The rather simple block/basin morphology of the Permo-Triassic was replaced in the Middle and Upper Jurassic by a more intricate mosaic of relative

highs and lows, based on the earlier fabric of WNW and NNW trending basement faults.

The change in the tectonic regime from the Triassic to the Jurassic has been related by many authors to the emplacement of a large rift dome in the central North Sea, centred on the Central Graben, and associated with a Mid-Kimmerian phase of rifting in N.W.Europe (Ziegler, 1982; Michelsen and Andersen,1983, Gowers and Saeboe,1985, Glennie,1986). The doming event is thought to have been synchronous with extrusive igneous activity in the Forties Volcanic Centre, at the triple rift intersection of the Outer Moray Firth, Viking and Central Grabens, and this spatial association of doming and rifting led to early hypotheses of mantle plume induced rifting in this area (Whiteman et al.,1975). The proposition of a large domal uplift is based mainly on truncation geometries on the rift shoulders, and on sourcing and transport parameters for the Middle Jurassic paralic sequences of the Viking Graben, the Sole Pit Trough, and the Yorkshire Basin (Leeder,1983). Ziegler(1982) has suggested from the amount of truncation of Lower Jurassic, Triassic and Permian sequences, that the structural relief across the dome may have exceeded 2000 metres across its axis in the Danish Sector. The erosion of the rift shoulders supposedly occurred during the Bajocian-Bathonian, at the same time as major deltas were prograding northwards into the Viking Graben, and southwards into the Sole Pit, West Netherlands and Yorkshire Basins (Ziegler,1982). However, much of the stratigraphic evidence for the emplacement of this dome is based on wells drilled in the crucial area of the Central North Sea. Studies based solely on well data are subject to limitations of areal distribution, and as has been discussed in previous sections, many wells are located on structural highs where local erosion associated with

fault block rotations results in many incomplete sequences. It is therefore vital, that regional truncation associated with large scale uplifts be distinguished from local truncation on rotational fault block apices. Seismic-stratigraphic evidence in support of the rift dome hypothesis is lacking, and one of the aims of this chapter is to assess the tectonic significance of Jurassic unconformities in the axis of the postulated dome.

Most of the wells penetrating Jurassic sediments in the Danish Central Graben are located in the Southern and Central Tail End Graben. Consequently, the main focus of this seismic-stratigraphic analysis is on these two segments. Fortunately, the seimic resolution of the thick Middle and Upper Jurassic sequences is excellent, and the intra-Jurassic sequence boundaries have been correlated over large parts of the Tail End Graben to form a chronostratigraphic framework. Intense syn-depositional faulting and rapid lateral facies and thickness changes across the major boundary zones of the basement mosaic limited the correlation of individual sequence boundaries to contiguous subsiding areas. It was possible, however, to erect local seismic-stratigraphic frameworks within individual sub-basins, and these were calibrated using the available well control.

2.6.1 The Lower Jurassic.

Lower Jurassic shales of the Fjerritslev Formation (Koch et al.,1982) were encountered in M-8, O-1, and U-1, located in the Southern Tail End Graben (Enclosure 2). These shales are dated as Hettangian-Sinemurian in the three wells (Robertson's Research,1984). They occur above the Winterton Formation, which is Rhaetian in age (Jacobsen,1982). The Winterton Formation has a remarkably uniform thickness in the three wells, ranging from 10 metres in M-8, to 14

metres in U-1. The preservation of a complete, though condensed section of the Winterton Formation beneath the Lower Jurassic, suggests that deposition was more or less continuous across the Triassic/Jurassic boundary. This conclusion is supported by the concordant relation observed between the Lower Jurassic and Upper Triassic on seismic data (e.g figure 2.9).

U-1, O-1, and M-8 were drilled on the crests of Zechstein pillow structures (Enclosure 2, figure 3.11). The Lower Jurassic is truncated towards the crests of the pillows at the Base Middle Jurassic unconformity (figure 2.9). Truncation geometries observed from the seismic data indicate that up to 100 metres of Lower Jurassic was eroded from these crestal areas. The erosion accompanied the earliest phase of growth of the pillows, which took place between the Sinemurian and the early Bajocian (figure 2.23).

The Lower Jurassic can only be identified with certainty on the seismic data close to the area of well control. The concordance of the Upper Triassic and Lower Jurassic sequences and the lack of any significant hiatus at the Triassic/Jurassic boundary suggests a close genetic relationship between the two sequences. It is therefore presumed that the Lower Jurassic is likely to be present wherever a complete Triassic sequence is preserved. The distribution of Lower Jurassic is assumed to have been similar to that outlined for the Triassic in figure 2.22. The maximum thickness of 150 metres observed in the rim synclines of the Southern Tail End Graben can be taken as an approximate upper limit for the sequence elsewhere in the Danish Central Graben.

2.6.2 Middle Jurassic.

The base of the Middle Jurassic is marked throughout the Tail End Graben by a laterally continuous, high amplitude reflection. This event corresponds almost exactly to the stratigraphic pick of the Base Middle Jurassic in several wells in the Southern Tail End Graben and the Sogne Basin (figure 2.23). In both these areas, the sequence boundary is a gently angular unconformity over the crestal parts of salt structures, passing laterally into a correlative conformity in the adjacent rim synclines and basinal areas (Enclosure 12, figure 2.9). In the Central and Northern Tail End Graben segments, there is minor angular discordance at the Base Middle Jurassic sequence boundary on the western margin, immediately adjacent to the Jens-Otto Fault Zone (Enclosures 13 and 15). The geometry of the truncation surface and its relationship to the overlying sequence suggest that the erosion of the western flank of the graben was the result of rotation and minor uplift accompanying the onset of more rapid fault controlled subsidence of the graben floor. The Base Middle Jurassic can be correlated across the Jens-Otto Fault Zone from the Central Tail End Graben, but it can only be traced over a limited part of the Dogger Platform (Enclosure 2). The Middle Jurassic and older sequences are truncated by the Upper Jurassic, and much of the pre-Upper Jurassic Mesozoic cover has been eroded from large parts of the Dogger Platform(figures 2.19 and 2.32). It is difficult, therefore, to estimate the original extent of Middle Jurassic deposition on the Dogger Platform.

A thin succession of interbedded shales and sandstones was drilled in Q-1, which is located on the apex of a rotated fault block on the northern flank of the Dogger Platform. This sequence was referred to the Middle Jurassic J-2 unit on lithostratigraphic grounds by Koch et al.(1982). However, recent biostratigraphic analysis of this sequence

suggests an Oxfordian age (Robertson's Research Report). This chrono-stratigraphic interpretation accords well with reports of a Late Oxfordian to Kimmeridgian age for a sequence with similar lithologies found unconformably overlying Late Carboniferous-Early Permian lavas in W-1 (figure 2.23). It seems probable, therefore, that these two sequences are part of a basal Upper Jurassic succession that is observed on seismic data to onlap a major truncation surface throughout the Dogger Platform.

The stratigraphic relationships of the Jurassic on the Dogger Platform derived from the well and seismic data are schematically illustrated in figure 2.27. Two alternative interpretations of the stratigraphy are presented in figure 2.28. In the first case(A), the Dogger Platform is portrayed as an area of pronounced Middle Jurassic erosion. Middle Jurassic uplift and erosion of the Dogger Platform has been invoked by Michelsen and Andersen(1983) and Gowers and Saeboe(1985), and related by these authors to the regional doming of the Central North Sea. In the second case(B), it is suggested that there was only limited tilting and peneplanation of the Dogger Platform prior to the Upper Jurassic. This is attributed to rotational subsidence of the Tail End Graben. This may have occurred during the hiatus represented by the Base Middle Jurassic sequence boundary. Following this gentle truncation, the Bajocian-Callovian sequence may have been deposited over the entire Dogger Platform, but the onset of rapid rotational subsidence resulted in a renewed phase of tilting and truncation in the Upper Jurassic (see Chapter 3.5). The erosion was most pronounced on horst blocks formed by the faulting which accompanied the larger scale tilting, and relatively complete sequences were preserved in the hanging

walls(e.g figure 2.19). Finally, the Upper Jurassic progressively onlapped the considerable relief of the truncation surface.

The lithofacies of the Middle Jurassic is fairly well constrained in the Sogne Basin and the Southern Tail End Graben. In both these areas, the sequence encountered in wells is a paralic succession of sandstones, claystones and thin coals, which is generally comparable with the Bryne Formation of the Norwegian Sector (Gowers and Saeboe, 1985). The sequence is much sandier in the Sogne Basin than in the Southern Tail End Graben, and this led Frandsen et al.(1987) to introduce the term Central Graben Group for this southern area. The two sequences are equivalent in age, and range from the Bajocian to the Callovian (figure 2.23). A sandy unit is found at or near the base of the penetrated sequence in wells in both areas (figure 2.23), and it is probable that the contact between the sandy unit and the dominantly shaly lithologies of the underlying Lower Jurassic or Upper Triassic gives rise to the characteristic high amplitude reflection.

The contrast in the Middle Jurassic lithofacies of the Sogne Basin and the Southern Tail End Graben is also apparent from the seismic expression of the sequence. In the Sogne Basin, the sequence is developed in a high amplitude discontinuous seismic facies (figure 2.25), whereas in the Southern Tail End Graben, the seismic facies is opaque to low amplitude and continuous (figure 2.9). The Bryne Formation has been interpreted as fluvio-deltaic (Koch et al., 1982), and the difference in seismic facies may simply reflect the relatively coarser nature of the sequence in the northern segment. There is no evidence of progradational reflection configurations anywhere in the Tail End Graben, that might be associated with the postulated axial delta system, prograding away from the domally uplifted source lands, and neither is

there any evidence for rapid influxes of coarser clastics from either of the margins of the graben. The reflection configurations are parallel on a local scale throughout the length of the graben, which implies that water depths were uniform in the basin, and that sedimentation and subsidence rates were closely balanced.

The pattern of thickness distribution differs from segment to segment. In the Sogne Basin and Central Tail End Graben segments, the Middle Jurassic thickens gradually towards the East. This is expressed in slightly divergent configurations and a gentle basal onlap in the Central Tail End Graben (Enclosure 15), and in divergence without onlap in the Sogne Basin (figure 2.25, Enclosure 12). The divergence is the result of rotational subsidence of the graben floor controlled by the Coffee Soil and the Gorm Faults. The thickness is uniform in the other two graben segments (Enclosure 13 and figure 2.9), and the parallelism of the faint internal reflections of the sequence implies that subsidence of the graben floor was horizontal throughout the deposition of the Middle Jurassic.

The Middle Jurassic is believed to be present in the Feda Graben, south-west of the Gert Ridge. The deeper stratigraphic succession can only be interpreted from the seismic data, since there are no deep penetrations in wells drilled in the Feda Graben. A parallel bedded sequence with high amplitude reflections reminiscent of the Bryne Formation is observed on seismic data in the deepest part of the graben (Enclosure 12, figure 2.21). This presumed Middle Jurassic sequence and the Triassic sequence are progessively truncated by the Upper Jurassic towards the Dogger Platform, and no direct correlation can be made with Q-1 or W-1. There is no evidence for any major erosion surface at the

base of this sequence, although there are occasional indications of a gentle basal onlap (figure 2.21).

A reconstruction of the depositional extent of the Middle Jurassic is presented in figure 2.29. The pattern is similar to that envisaged for the Triassic and Lower Jurassic (c.f figure 2.22). It is speculated that the Middle Jurassic was originally deposited over the entire Dogger Platform-Feda Graben area, possibly after a limited phase of gentle truncation of Lower Jurassic and Triassic strata. The absence of any significant coarse detritus in the Middle Jurassic drilled in the Southern Tail End Graben, or of any seismic indications of alluvial fan or deltaic progradation on the margins of the Dogger Platform argues against the idea that the Dogger Platform (Vigeland Ridge of Gowers and Saeboe,1985) was subjected to major uplift and erosion as part of the postulated Mid-Kimmerian tectonic phase (Michelsen and Andersen,1983, Gowers and Saeboe,1985). The stratigraphic relationships on the Dogger Platform are instead attributed to an Upper Jurassic phase of tilting, faulting and erosion, accompanied in places by progressive onlap and overstep of Oxfordian to Volgian sequences.

2.6.3 The Upper Jurassic.

A major change in the basin framework took place at the transition from the Mid to Late Jurassic. Basement faults that had been active during the Triassic and Middle Jurassic continued to be the main locus of differential vertical motions and major controlling elements for the deposition of the Upper Jurassic. However, the rates of displacement were much higher than previously, and in addition there was a polarisation towards more rotational patterns of subsidence in the fault bounded basins. The floors of the earlier grabens became dissected by complex fault zones, that in part reactivated pre-existing and long

dormant structures, and these served to divide the Danish Central Graben into a series of rhombohedral fault bounded blocks that subsided at different rates throughout the period. The complex and laterally varying stratigraphy of the Upper Jurassic can be understood in fairly simple terms as the interplay of a mosaic of differentially subsiding fault blocks with minor fluctuations in absolute sea level and clastic supply.

The structural framework and generalised subsidence patterns during the Late Jurassic are reconstructed from the isochore data and from analysis of reflection configurations. The reconstruction is illustrated in figure 2.30. Divergent reflection configurations characterise the Upper Jurassic sequence in the north-eastern Feda Graben, and the Central and Tail End Graben segments. In each of these areas, the sequence thickens towards the low angle basement faults controlling the basin margins (Enclosures 8 and 9). Several local onlap surfaces are observed on the convergent flanks of the rotated graben floors (Enclosures 12 and 13). These indicate either an imbalance between sediment supply and subsidence across the rotationally subsiding graben floor, or the superposition of absolute changes of sea level during a phase of constant sediment supply.

The thickness of the Upper Jurassic in the south-western Feda Graben is comparable to that measured adjacent to the Mandal Fault in the north-eastern block (Enclosure 9), but the reflection configurations differ in that they are parallel or only gently divergent (figure 2.31). This suggests that the two halves of the Feda Graben subsided differentially, by fault block rotation in the north-east, and horizontally in the south-west. The horizontal subsidence of the south-western block was controlled by the large basement fault on the

margin of the Lindesnaes Ridge, and a series of step faults leading up to the Gert Ridge (Enclosure 12, see Chapter 3.5).

The original depositional relationships of the Upper Jurassic in the Sogne Basin are difficult to reconstruct because a significant proportion of the sequence was eroded in the Late Jurassic and Early Cretaceous, during rotational uplift of the Mandal High. The uplift was coeval with rotational subsidence towards the Coffee Soil Fault, and took place some time between the Late Jurassic and the Late Cretaceous. There is severe truncation at the Base Cretaceous unconformity (Enclosure 12), and in Lulu-1, Santonian chalks rest unconformably on middle Volgian shales (figure 2.23). The lower part of the Upper Jurassic sequence is parallel bedded, but rotational thickening can be seen in the divergent upper part of the sequence immediately adjacent to the Coffee Soil Fault, where there is no angular unconformity at the Base Cretaceous sequence boundary (figure 2.25). On close examination, the divergent upper part of the sequence is seen to be expressed as a series of lobate progradational bodies clustered against the fault scarp. The change in reflection configurations from parallel to divergent is suggestive of a two-stage subsidence history comprising an early horizontal subsidence, controlled by the margin faults but possibly encompassing a large fault block, followed by rotation, tilting, erosion of the uplifted western margin (the Mandal High), and progradation into the water depth created by the rapid subsidence at the foot of the hanging wall (figure 2.25). The structural complexity in the vicinity of the Lulu-1 well prevents a direct calibration of the seismic data, and it is not possible to constrain the timing of these two phases.

The Upper Jurassic is relatively thin in the Southern Tail End Graben as compared with the other segments of the Tail End Graben

(Enclosures 8 and 9). The isochore maps depict a complex pattern of ellipsoidal thickness maxima and minima. These local variations in thickness are related to the syn-depositional growth of Zechstein salt structures(e.g figure 2.9, Enclosure 18). The Oxfordian and Kimmeridgian do not thin appreciably across the salt pillows, and most of the thickness variation is expressed in the Volgian sequence. The Base Volgian is a prominent sequence boundary throughout Tail End Graben. In the Southern Tail End Graben, it is marked by a strong basal onlap on to the flanks of the salt pillows. This onlap is interpreted as tectonic, as it is clearly related to the onset of uplift and growth of relief of the salt structures. When the localised effects of halokinesis are filtered out, the thickness of the Upper Jurassic in the Southern Tail End Graben is found to be remarkably uniform. the gross reflection configurations are parallel, and it is concluded that subsidence of the graben floor was moderate in rate and horizontal in form.

The Dogger Platform behaved as a relatively stable block during the Late Jurassic. The average thickness of the Upper Jurassic is less than that observed in the Sogne Basin or the Southern Tail End Graben, and is more comparable with the axial part of the Feda Graben (Enclosure 9). The thickest sequences occur in small fault blocks, and on the eastern flank adjacent to the Tail End Graben. The base of the Upper Jurassic sequence is a major erosional unconformity (figure 2.19). This unconformity is onlapped by shallow marine or coastal sandstones dated as Oxfordian in W-1, and late Oxfordian to Kimmeridgian in Q-1 (Robertson's Research, 1984). The pronounced relief on the onlapped basal unconformity, and the truncational relationship with the underlying Middle Jurassic and Triassic sequences (figures 2.19, 2.32) suggests that there was a major phase of emergence and erosion, and

possibly uplift, during the later part of the middle Jurassic and the early part of the Upper Jurassic (figures 2.27 and 2.28). The paucity of well control means that the duration of this hiatus is not tightly constrained, and the matter is further complicated by the common superposition of successive phases of erosion on many of the apices of the rotated fault blocks. As argued previously, however, the increase in clastic supply into the grabens occurred in the Late Jurassic, rather than the Middle Jurassic, which is compatible with the envisaged Callovian to early Oxfordian phase of erosion on the Dogger Platform (figure 2.28).

Divergent reflection configurations are commonly observed within small fault blocks, and these imply that the faults were active in a rotational sense during the Late Jurassic. On the tectonically stable Dogger Platform, any such rotation of the hanging walls of these fault blocks would automatically have resulted in periodic emergence of the apices. During relative low-stands, these emergent apices would have been particularly vulnerable to erosion, and they may have been important local sources of sediment supply (figure 2.33). There are several intra-formational unconformities in some parts of the Dogger Platform, which are of local extent, and can not be tied to either of the control wells. They are often surfaces of truncation and onlap, and are invariably associated with horsts or rotated fault blocks (figures 2.19 and 2.32, Enclosures 13 and 14). These truncational local unconformities were probably produced during phases of relative low stand. The relative stability of the Dogger Platform probably favoured the development of such local unconformities, since any temporary fluctuation in relative sea level due either to fault block rotation and uplift, or sea level fall, would have produced topographic features in the high energy coastal zone, and erosive processes would necessarily

have been dominant. The elevated parts of horsts and rotated fault blocks were probably maintained near or above erosional base level for much of the period, but accelerated fault rotation or eustatic sea level changes may have led either to temporary submergence and onlap, or to emergence and erosion (figure 2.33).

2.6.4 Lithostratigraphy, Seismic Facies, and Palaeogeographic Reconstruction of the Upper Jurassic.

The framework of differentially subsiding blocks was of paramount importance in the organisation of the depositional systems of the Upper Jurassic. In the rapidly subsiding graben segments (figure 2.30), the Upper Jurassic is characteristically developed in a low amplitude, continuous seismic facies. Individual reflections are correlatable for large distances along dip and strike lines, which suggests a uniformity of depositional process over large areas. The reflections are internally concordant, and this implies either a drape of an inclined depositional surface or drape or directed deposition on an horizontal depositional surface (Vail et al.,1977). Reflection forms and seismic facies normally indicative of high energy depositional systems are entirely absent from the deep graben areas, and the uniformity of the low-energy seismic facies throughout the extremely thick successions implies persistently balanced subsidence and sediment supply rates.

In the deeper parts of the Central and Northern Tail End Graben segments, however, the generally opaque or low amplitude sequence is punctuated at intervals by high amplitude, continuous reflections that emanate from thin interbedded dolomite or limestone horizons. These pelagic carbonate layers were deposited during periods of severely reduced clastic input into the basin, possibly during relative highstands of sea level, when the marginal source areas would have been

drowned. Unfortunately, there are too few wells available to attempt a basin-wide correlation of these interbedded carbonates, and their chronostratigraphy is poorly defined. Some of these high amplitude, conformable reflections correlate with onlap surfaces in the convergent sequences of the hinged basin margins (figure 2.40). In a classical sense, each of these onlap surfaces represents a relative rise of sea level, and their equivalence with periods of reduced clastic input and increased pelagic deposition in the basinal areas raises the possibility of their being of basin-wide significance. If the onlap surfaces were solely tectonic in origin, there would be no particular reason for there to be a correlation with the change in the deeper marine depositional systems. On the contrary, a 'tectonic' onlap of the basin margins would normally be equated with an increase in the rate of subsidence in the basinal graben areas, and this might be expected to <u>increase</u> the supply of derived clastics. It seems probable, therefore, that the onlap surfaces resulted from a basin wide rise in sea level superimposed on the tectonically hinged margin. Unfortunately, the ages of these onlap surfaces are poorly constrained, and it has not been possible to refer them to charts of global change of relative sea level.

The deep graben succession is over 4000 metres thick in the Northern Tail End Graben adjacent to the Coffee Soil Fault, and over 2,500 metres thick in the north-eastern block of the Feda Graben, adjacent to the Mandal Fault (Enclosures 8 and 9). The only significant well penetrations are E-1 and 2/11-1. The lithologies encountered in these and other, more limited penetrations were predominantly claystones, with minor siltstone and carbonate intercalations (Koch et al., 1982). The Upper Jurassic claystone sequences are referred to as the J-3 and J-4 units (Koch et al.,1982), or the Lola and Farsund

Formations (Frandsen et al.,1987). These lithostratigraphic subdivisions are presented in figure 2.34. They have been interpreted as having been deposited on the outer marine shelf (Koch et al.,1982), either from suspension or by some process of redeposition, under generally open marine conditions and amidst a background of high organic productivity (Frandsen et al.,1987).

The uppermost part of the Farsund Formation (latest Volgian to Ryazanian) is occasionally associated with high gamma ray values. The lithology of this 'hot shale unit' is similar to the non-radioactive Farsund Formation in all respects save the content of organic carbon. The profuse quantity of organic carbon in the 'hot shales' is believed to be the result of a period of restricted bottom circulation (Frandsen et al.,1987), and some authors have related this anoxic period to a eustatic fall in sea level at the end of the Jurassic (Rawson and Riley, 1982).

Seismic-stratigraphic analysis of the Upper Jurassic sequence suggests, however, that deposition in the rapidly subsiding graben segments took place in slope or basin floor settings, at depths considerably in excess of those suggested in previous interpretations. Estimates of the bathymetry from the shelf to the basin floor can be made from the geometry of progradational sigmoidal reflections, in accordance with the principles laid down in Vail et al.(1977). Sigmoidal reflection configurations are observed from the Kimmeridgian and Volgian sequences in the Central Tail End Graben, and the direction of progradation is away from both the stable platform-type area of the Southern Tail End Graben and the bordering Ringkobing-Fyn High (Enclosures 18 and 19). High amplitude/high frequency topset reflections

build upwards and outwards from a structural break of slope or tectonic hinge zone located along the Dan Transverse Zone (see Chapter 3.2.4).

The structural break of slope coincides with a rapid northward thickening, particularly of the Volgian sequence, and it is inferred that the shelf/slope break was controlled by the hinge-type behaviour of the transverse fault zone. This concept is illustrated in figure 2.35. The topsets correlate downflank with the low amplitude, continuous seismic facies of the rapidly subsiding Central Tail Graben. The only occasional downlap of the bottomset reflections on to the horizontal and parallel bedded basin floor is typical in the progradation of a fine grained system during a phase of rapid relative rise of sea level (Vail et al.,1977). A rapid relative rise of sea level can also be inferred from the topset geometry, from the lack of erosion or by-pass on the outer part of the shelf (figure 2.36). The relief on individual topset-foreset-bottomset reflection events is of the order of 200 to 300 metres. When this figure is corrected for compaction, it suggests original sea bottom relief of between 500 and 600 metres, and depositional slopes with gradients of around 5 degrees (figure 2.37). This pronounced bathymetric variation along the axis of the Tail End Graben, was undoubtedly the result of differential subsidence. The stably subsiding Southern Tail End Graben was a muddy shelf throughout the Late Jurassic, whereas the two central segments formed a deep basin plain. The sediments deposited on this horizontal or gently inclined basin floor, were probably admixtures of fine grained turbidites derived from the shelf edges, and pelagic clays, silts and carbonates.

An interesting feature of the hinge zone is the development of multiple onlap surfaces in the Volgian sequence similar to those seen on the other hinge-type margins around the Tail End Graben (Enclosures 13, 14, and 18). The resolution of the onlap surfaces is particularly sharp because of the rapid lateral expansion in the thickness of the sequence as a whole. On less steeply inclined slopes, genuine stratal onlaps can often appear as concordant or gently divergent reflection configurations, and in these circumstances, it is often difficult to distinguish genuine onlap from reflection termination resulting from decrease in bed thickness below the limit of vertical resolution (figure 2.38). The multiple onlap surfaces developed on the slope are indicative of several discrete periods of relative sea level rise. As with the previously described hinge bordering the Dogger Platform, these onlap surfaces also correlate with the basinal high amplitude reflections, but it has not been possible to establish whether or not the onlap surfaces on all three hinged margins are synchronous. It is evident from the gross changes in reflection configurations from segment to segment along the Tail End Graben, that there was considerable lateral variation in the rates and timing of displacement along the Coffee Soil Fault (Chapter 3.2.3). It is probable, therefore, that there would have been a corresponding diachroneity in the tectonic component of the stratigraphy of the hinged margins. Better well control may, in future, allow a more tightly constrained basin-wide correlation of the various intra-Upper Jurassic unconformities, and this in turn may permit the 'eustatic' and 'tectonic' components to be filtered from the combined signature. The only conclusion that can be drawn at present, is that the onlapped hinges are a product of the tectonically controlled differential

subsidence, and the background variations in the nature of the sediment supply.

There are minor differences in the shelf-slope-basin floor association of the divergent sequence configurations across the western and northern hinged margins of the Tail End Graben. The western margin differs in that there are no obvious indications of shelf progradation from the Dogger Platform outwards towards the deep basinal graben. There is, however, a marked difference in seismic facies on either side of the structurally complex Jens-Otto Fault Zone, from the continuous, low amplitude facies of the divergent sequence, to the discontinuous, high frquency/variable amplitude facies in the more parallel bedded sequence on the Dogger Platform (Enclosures 13 and 14). This change in seismic facies is interpreted as marking the shelf/slope transition. The discontinuity of the reflections on the Dogger Platform is indicative of a high energy depositional setting with rapid lateral variations in lithology, whereas the continuity of the reflections on the flank of the Tail End Graben is indicative of greater homogeniety of lithofacies and lower energy depositional environment. Shallow marine to coastal sands and shales comprise the shelf sequence on the Dogger Platform as proven in W-1 and Q-1, whereas the divergent sequences encountered in I-1 and E-1, are developed in the homogeneous, organic rich claystones of the basinal lithofacies. Coarser grained lithologies are surprisingly absent from wells drilled immediately to the east of the Jens-Otto Fault Zone, which suggests that the products of erosion of the intermittently emergent horsts on the Dogger Platform were confined to the nearby shelf areas, and were not transported across the structurally controlled shelf/slope break (figure 2.39). It is remarkable, for example, that there is no evidence of sandy turbidites deposited on the slope during

low-stands when the shelf would have been largely emergent. In models of deep marine onlap of slopes following a relative low stand of sea level,the shelf is portrayed as an area of by-pass and erosion, with rivers cutting deeply into the shelf sequences, and transporting the products to incised canyon heads at the shelf/slope break (e.g Vail et al., 1977). The deep marine onlap is interpreted in these models as the apron of submarine fan deposits fed from the shelf via the canyons. One reason for the absence of such low-stand deposits adjacent to the margin may be that the active faults on the shelf prevented the longer range transport of products from the erosion of up-tilted fault blocks to the shelf edge, and formed local sediment traps in the interior of the shelf (figure 2.33). During the periods of relative rise of sea level indicated by the repeated onlaps onto rotated fault blocks within the Dogger Platform, local highs would have been drowned, shorelines would have retreated towards the flanking highs, and the low-stand coarse clastics would have been reworked within fault bounded depressions. This is only one possible explanation for the confinement of sands to the Dogger Platform, and other factors such as bathymetry and wave energy may also have been important.

The northern margin of the deep basinal part of the Tail End Graben is also structurally controlled, and is comparable with the southern margin, in that the shelf/slope break, and the position of the depositional hinge coincides with a graben segment boundary, which in this case is the Lulu Transverse Zone (see Chapter 3.2.4). The Upper Jurassic thins rapidly across the intensely faulted structural hinge, and there is a corresponding change from a basinal low amplitude, continuous seismic facies to a high frequency, variable amplitude, discontinuous facies across the structural hinge zone on to the more

stable Sogne Basin segment (Enclosure 18, figure 2.40). The discontinuous seismic facies is calibrated in Lulu-1 and 3/5-2, where it is found to comprise a sequence of shallow marine sandstones and claystones. It is concluded that the Sogne Basin formed a shallow marine shelf for much of the Late Jurassic, by virtue of the relatively stable subsidence of this graben segment.

The gross reflection configurations of this margin are similar to those described from the western and southern margins, and conform to the generalised model for the structural siting of the shelf/slope break (compare figures 2.35 and 2.39 with figure 2.40). In detail, however, there is an important difference in the configurations and the depositional systems of the shelf and slope along this northern margin. Mounded, progradational reflection configurations can be seen on seismic data immediately downslope from the shelf edge. These prograding bodies appear as lensoid forms when viewed across depositional strike, display pronounced downlaps in a direction perpendicular to the scarp of the Coffee Soil Fault (figure 2.41), have truncated and onlapped upper surfaces, and exhibit rapid changes in morphology along and across depositional strike. From the reflection geometries of the prograding units, and their occurrence adjacent to the fault scarp, it is suggested that these units represent a stacked series of gravity flow deposits (slumps, debris flows, submarine fans or fan deltas), that were derived locally by erosion of the fault scarp, and prograded directly into a deep marine basin at the foot of the large relief submarine scarp (figures 2.39 and 2.41). The Lower Permian and older sequences are severely truncated along the shoulder of the rift at the edge of the Ringkobing Fyn High (figure 2.42), and it is probable that the Late Jurassic mounded units are largely composed of the products of these

truncated sequences. As such, they may well contain significant proportions of reservoir quality sandstones, but in view of the extreme discontinuity of individual reflectors within the lobate sequences, the lateral continuity of any reservoirs is unlikely to be favourable for exploitation. Comparable sequences have been described from the Upper Jurassic along the border faults of the Viking Graben (Stowe et al., 1982), and development drilling has confirmed the rapid lateral discontinuity of the reservoir units.

Progradational mounded and lensoid forms are observed in only two places along the c.100 kilometer length of the Coffee Soil Fault. The most significant occurrence in volumetric terms, is that described above from the offset scarp margin at the intersection of the Lulu Transverse Zone. The other area where these reflection forms have been observed immediately adjacent to the fault scarp is also at an offset portion of the Coffee Soil Fault, at the intersection of the Adda Transverse Zone (figure 2.43). Late Jurassic to Early Cretaceous sandstones encountered in V-1, drilled in the midst of the prograding seismic facies only 3 kilometers from the fault offset, were interpreted by Frandsen et al.(1987) as having been deposited from turbidity currents. The localisation of high energy scarp related depositional systems to the points of maximum structural disruption of the fault plane and footwall, is viewed here as the consequence of erosional exploitation of the highly fractured parts of the crystalline footwall rocks in preference to the undeformed rift shoulders. This concept is illustrated schematically in figure 2.43. The influence of transverse fault structures on the siting of fault scarp fan systems, has also been reported from carbonate depositional systems in the Carboniferous Bowland Basin of Northern England (Gawthorpe, 1987), and has been

discussed in a wider context of half-graben depositional controls by Leeder and Gawthorpe(1987).

A generalised palaeogeographical reconstruction of the Danish Central graben during the Late Jurassic is presented in figure 2.44. This reconstruction is based on mapping of the distribution of the various seismic facies described above, and integration of the lithostratigraphic analyses of the released wells. Four depositional provinces are recognised:-

(1)Basin Floor. This province is characterised by low amplitude/continuous seismic facies, intermittent high amplitude pelagic carbonate reflections, and divergent or parallel reflection configurations. This association is recognised in the rapidly subsiding flanks of the Feda Graben, adjacent to the boundary faults, and in the two central segments of the Tail End Graben.

(2)Slope. The seismic facies of the slope province are similar to those of the basin floor. The two provinces are distinguished by the convergent and often onlapping reflection configurations of the slope, and the occasional development of progradational sigmoidal or lobate reflection geometries. The deep basinal areas are flanked on the hinge-type margins by clearly defined slope associations. The major fault bounded margins were major topographic features on the sea floor, and submarine relief across the fault scarps may have exceeded 500 metres in places. The steep gradients of the sea floor on the scarps prohibited the formation of slope aprons everywhere except at the intersections of the transverse segment bounding fault zones, where the supply rates locally exceeded the subsidence rates. Along the remainder of the fault traces, the scarps were onlapped directly by dominantly

distal turbiditic clays transported from the adjoining shelves (figure 2.43).

(3)Marine Shelf. This province is characterised by a high frequency, variable amplitude and discontinuous seismic facies, and by generally parallel sequences. Intraformational unconformities of limited areal extent, with truncated lower and onlapped upper surfaces, are additional indications of fairly shallow marine conditions with temporary phases of emergence, erosion, and reworking.

(4)Terrestrial/Non Depositional. The Upper Jurassic is entirely absent on the flanking Mid North Sea and Ringkobing-Fyn Highs, and over parts of the Dogger Platform, Dogger High and Mads High. It is not known whether these highs were fully emergent throughout the Late Jurassic, or whether they were occasionally submerged during eustatic high stands of sea level (Vail and Todd,1981). Truncation geometries on the rift shoulders indicate that up to 1000 metres of Lower Permian and older sequences were eroded (figure 2.42), but this net uplift and erosion could have taken place at any time between the Late Permian and the Late Cretaceous. Stratigraphic relationships in the Mesozoic on the northern margin of the Ringkobing-Fyn High indicate that most of the region was at or near sea level throughout the Triassic and Jurassic (Chapter 4). The absence of major truncational unconformities post-dating the mega-truncation event in the Late Carboniferous-Early Permian rules out the possibility of any significant topography over the area during the Mesozoic. It is probable that the flanking highs were low, flat lying areas, peneplained immediately after the major Late Carboniferous uplift, and remained thereafter as stable, non-subsiding blocks. The rift shoulders may have been areas of gentle upwarp, subject to slow erosion. Persistent and slow footwall uplift, coeval with active fault

controlled subsidence in the grabens, rejuvenated these shoulders and maintained them as a source of minor clastic input. Acceleration of fault motion in the Late Jurassic probably exacerbated this marginal relief, and provided the impetus for increased coarser clastic deposition on the scarp aprons.

The intra-basinal horsts were probably low-lying islands during eustatic falls of sea level, and partially or wholly submerged shallow banks during high stands. Older Mesozoic and Late Palaeozoic sediments may have been intensely reworked during high stands in the high energy hydraulic conditions of the shallow shelf and coastal belt, and then shed into the neighbouring fault bounded shelf depressions during low stands.

In conclusion, the following points are emphasised. The depositional systems were primarily influenced by the fault bounded block-basin morphology of the subsidence patterns. The basin margin geometries and sea floor topography were a direct reflection of the style of the controlling structure. Hinged structures and transverse fault zones at segment boundaries formed depositional hinges with broad slopes separating stable platfoms and rapidly subsiding basin floors. Steep, submarine fault scarps with considerable relief marked the narrow basin-platform transition along the major fault bounded margins.

2.7 THE LOWER CRETACEOUS.

The Lower Cretaceous has been described in detail recently by Vejbaek(1986), and is only considered briefly in this section. Vejbaek's(1986) account of the Lower Cretaceous is based on a seismic-stratigraphic interpretation, together with petrophysical evaluations of released wells. He presented isopach maps of six,

seismically defined sub-sequences. No attempt was made to define a chronostratigraphic framework for the sequence subdivision, because of the limitations of the biostratigraphic resolution.

The isochore map presented in Enclosure 10 is broadly similar to the gross Lower Cretaceous isopach map published by Vejbaek(1986). The only significant departure concerns the interpretation here of a thick sequence of Lower Cretaceous in the Outer Rough Basin, south-west of the Olaf Fault Zone (figure 1.3). Both Vejbaek(1986) and Gowers and Saeboe(1985) regard the infill of the small hanging wall basins as Late Jurassic in age. There are no released wells in this area, but the seismic character and sequence geometry is identical to the thick Lower Cretaceous sequence on the south-western block of the Feda Graben, and this jump correlation is taken accordingly as the basis for the preferred interpretation of an Early Cretaceous age (c.f Enclosures 12 and 13).

The Lower Cretaceous occurs in a number of small, elliptical sub-basins (figure 2.45). These sub-basins are located along the faulted margins of the Late Jurassic depocentres, and a comparison of Upper Jurassic and Lower Cretaceous isochore maps reveals a close correspondence between the isochore maxima of the two sequences (Enclosures 9 and 10). Recognition of this overlap of depocentres led Vejbaek(1986) to propose that the 'dextral conjugated wrench faulting' proposed for the Late Jurassic by Gowers and Saeboe (1985), continued during the Early Cretaceous (figure 2.46). A contrasting view of Early Cretaceous basin development is taken here, whereby the deposition in the various sub-basins is instead attributed to a post-tectonic phase of basin infill, with essentially non-tectonic complementary processes of

sediment loading and compaction as the only significant causes of vertical motion of the depositional surface.

Representative line drawings showing the detailed reflection configurations of the Early Cretaceous sub-basins are presented in figure 2.47. The most striking observation to be made from the Lower Cretaceous reflection configurations in the sub-basins, is that the margins of the sub-basins are progressively onlapped, and the direction of the onlaps is radial, away from the axes of maximum thickness (figure 2.45). In cross section, the onlap configurations can be defined as parallel basin fill. The stipulations for this are that the internal onlapping strata are concordant with the upper sequence boundary, and there is no appreciable internal divergence (figure 2.48). There are two exceptions to this otherwise general configuration. The first is along the fold above the Gorm Fault Zone (figure 2.47d, Enclosure 16), and the second is along a pop-up structure in the Northern Tail End Graben (Enclosure 13). In these two cases, the onlaps were modified by syn-depositional uplift of the fold crests, and the early onlapping units were tilted into near concordance with the basal Cretaceous sequence boundary (figure 2.48). Later compaction can also produce onlap geometries similar to those equated with growth folding or faulting (figure 2.48), but compactional and structural modifications can be distinguished by reference to the structural setting. The planar contacts of the onlapping reflections on the margins of the Feda and Tail End Grabens, and the Outer Rough Basin show surprisingly little evidence of compactional warping, and angular contacts of up to 10 degrees are preserved in some cases (figure 2.47).

The stratigraphic and tectonic significance of this parallel onlap fill of the Lower Cretaceous is crucial to the analysis of the Late

Jurassic and Early Cretaceous basin development of the Central North Sea, and has important implications for thermal models of the Late Cretaceous and Tertiary subsidence in the region. The only possible interpretation of the parallel onlap geometries is that the Lower Cretaceous represents the progressive infill of pre-existing topography of the basin floor. Had the sub-basins formed by active basement faulting, the onlapping units would diverge towards the faulted margins. Similarly, if the void now represented by the Lower Cretaceous fill had developed progressively by protracted subsidence of the substrate, the early onlapping units would have been deformed in harmony with the basal sequence boundary. Neither of these styles of onlap configuration is apparent on the seismic data (figure 2.32). It is concluded, therefore, that all the relief expressed in the onlapped faulted and hinged margins was established prior to the earliest onlap.

In each of the sub-basins, the sequence boundary at the base of the onlap fill is concordant with the Upper Jurassic sequence, and there is no indication on the seismic data of any erosion before the beginning of the onlap fill. On the rift shoulders, the Base Cretaceous sequence boundary is a major truncation surface, juxtaposing onlapping or condensed Lower Cretaceous sediments with Upper Palaeozoic sediments or crystalline basement. The truncation surface represents the cumulative erosion of the rift shoulders throughout the evolution of the rift, and can/not be attributed specifically to tectonic events at the transition from the Jurassic to the Cretaceous. The prominent angular truncation at the Base Cretaceous over the Mandal High can, however, be directly related to a tectonic 'event', namely that of Late Jurassic and possibly Early Cretaceous rotation of the Sogne Basin fault block accompanying

active basement faulting on the Mandal and Coffee Soil Faults (Enclosure 12). This pre-Santonian uplift and erosion of the Mandal High is one of the very rare examples of a demonstrably structurally controlled non-sequence between the Jurassic and the Cretaceous. On the Dogger Platform, the Lower Cretaceous is extremely thin, but where the high amplitude basal sequence boundary is resolved separately from the Base Upper Cretaceous event, it is invariably found to be concordant with the Upper Jurassic (figure 2.19). In Q-1, the condensed Lower Cretaceous sequence was found to be almost complete, but in the P-1 and W-1, the Lower Cretaceous is absent. These two wells are located on horst blocks, and it is believed that their topographically elevated positions may have been responsible for the development of the non-sequences (figure 2.50).

The seismically defined Base Cretaceous sequence boundary thus changes from a correlative conformity at the base of the basinal onlap fill sequences, to an erosional unconformity of unknown duration over the rotated Mandal High, and to a primarily non-erosional base to a condensed sequence on the Dogger Platform. Such lateral variability raises a number of questions concerning the duration of erosional events and the relationship between changes in absolute sea level and changes in tectonic subsidence. Does the sequence boundary always separate older from younger strata, for example, and can tectonic and eustatic signatures be distinguished?

The Base Cretaceous 'unconformity' is widely developed in the area of the North Sea Rift. Ziegler(1982) has suggested that it represents a major regional erosional break corresponding to the Late Cimmerian tectonic pulse. This tectonic pulse is supposed to mark the onset of a phase of rifting in the N.Atlantic-N.W.European domain (Ziegler,1982).

The tectonic/eustatic significance of the Base Cretaceous 'event' has been widely debated, and in some of the arguments over this sequence boundary lies a labyrinth of confusion and disagreement over the origins of major, regional sequence boundaries (see for example, Miall,1986). Some researchers consider that the tectonic significance of the Base Cretaceous sequence boundary has been over-emphasised, and that the common assumption of a major stratigraphic break at the Jurassic/Cretaceous boundary does not apply over much of the North Sea (Hancock,1983). Rawson and Riley (1982) were impressed by the continuity of deposition across the boundary in basinal areas, and viewed the sequence boundary as the product of a eustatically controlled change in bottom circulation patterns, from the anoxic lowstand conditions of the the Volgian/Ryazanian, to the more oxygenated and open marine conditions resulting from the early Valanginian rise in sea level.

In the Danish Central Graben at least, there is no evidence whatsoever to suggest that the Base Cretaceous sequence boundary marked the onset of a renewed phase of rifting. On the contrary, the widespread onlap of buried fault scarps along the margins of the Late Jurassic depocentres (figure 2.47) suggests instead that the sequence boundary represents the end of active regional extension. Small offsets of the Base Cretaceous are apparent along parts of the major basement faults (Enclosure 10, figure 2.47). These offsets appear at first sight to imply small amounts of growth faulting on the basement structures during the Early Cretaceous, but identical bedding geometries would have been produced if the basement displacement had ceased in the Late Jurassic, and large remnant fault scarps were then onlapped passively during the latest Jurassic and Early Cretaceous (figure 2.49). There was certainly a limited degree of growth faulting along the Jens-Otto Fault Zone, but

it is difficult to conceive that the small fault offsets on the basin bounding faults constitute a regional resurgence in rifting as believed by earlier researchers (Ziegler,1982; Michelsen and Andersen,1983; Gowers and Saeboe,1985). The interpretation of the tectono-stratigraphic relationships expressed at the Base Cretaceous sequence boundary at the basin margins proposed here, is that of basin deepening due to the Late Jurassic acceleration of fault displacement, and passive onlap of extant fault scarps (figure 2.49).

The stratigraphic significance of this sequence boundary has been made clearer by a recent detailed biostratigraphic investigation of a continuous Jurassic to Cretaceous sequence drilled in a basinal position in the Central Tail End Graben (Birkelund et al.,1983). This study of the E-1 well shows that there was no significant hiatus across the Jurassic/Cretaceous boundary. The high amplitude reflection forming the base of the onlap fill succession ties in this well with a major lithological boundary between the Farsund and Valhall Formations. The lithology changes upwards from the organic rich black shales of the Farsund Formation to the grey shales of the Valhall Formation. This has been attributed to a change to more open marine bottom circulation patterns and increased oxygenation of the bottom waters (Koch et al.,1982; Frandsen et al.,1987), and this has been related in turn by Rawson and Riley (1982), to a eustatic rise in sea level. The lithological break, and hence the sequence boundary, has been dated by Birkelund et al.(1983) as the Valanginian/ Hauterivian boundary. The Base Cretaceous sequence boundary should, therefore, in this area at least, be more properly referred to as an intra-Lower Cretaceous sequence boundary. Since this seismic event corresponds to a change in marine chemistry, it is reasonable to assume that the high amplitude

reflection marking the basal sequence boundary in the other sub-basin axes also corresponds to this change in marine chemistry, and as such represents a geologically instantaneous event. If this is indeed the case, then it implies that the sub-basin morphology of the graben floor was established at some time before the Hauterivian. How, then, can this differential relief be explained, and what, if any, is the tectonic significance of the stratigraphic relationships at the transition between the Jurassic and the Cretaceous?

The basin floor relief expressed in the parallel onlap configurations ranges from 200 to nearly 600 metres (figure 2.47). If the interpretation of parallel onlap fill is correct, it necessarily implies that the lowermost onlapping Lower Cretaceous sediments were deposited in water depths in excess of 600 metres after active basement faulting had ceased. This value for the Early Cretaceous water depth in the axis of the rift is considerably larger than previously imagined, but fault scarps up to 1000 metres high are onlapped by deep marine Lower Cretaceous shales along the borders of the Viking Graben (Ziegler,1982). A similar order of magnitude of scarp relief along the Coffee Soil Fault is entirely reasonable given the extremely rapid Late Jurassic displacement on the fault, and the relatively much lower rates of sedimentation that would be expected in the fine grained clastic depositional system. Wells located on the rift shoulders (e.g L-1) and on the Dogger Platform (Q-1) encountered complete, but highly condensed Lower Cretaceous sequences, developed in pelagic claystone, marlstone and limestone lithofacies. The completeness of these condensed sequences implies that the shoulders and intra-rift highs must have been maintained well below storm wave base throughout the Early Cretaceous.

Allowing for minor fluctuations in absolute sea level during this period, it is probable that the water depths in the non-subsiding areas of the rift environs were at least 200 metres, giving an upper limit of perhaps 800 metres for the water depths in the deepest of the sub-basins (figure 2.50).

The first interpretation of the depositional environment of the basinal Valhall Formation referred to deposition in a the neritic zone (Hansen and Buch,1982). More recently, however, several authors have drawn attention to the importance of gravity flow processes in the deposition of the Valhall Formation with the inference that deposition took place in a slope or basin floor setting (Frandsen et al.,1987; Vejbaek, 1986). Thin fining upwards sequences, high contents of terrigenous organic matter, and the common occurrence of reworked Triassic and Jurassic microfossils have been cited in support of this interpretation of gravitational depositional processes. Seismic facies analysis indicates that the contribution of gravity deposits was most significant early in the period (Vejbaek,1986). The increase in the proportion of carbonates and marls upward through the succession is also indicative of a change to more pelagic modes of deposition and a lessening of the input of gravity flow deposits through the period (Frandsen et al.,1987). In addition, recent investigations of the Lower Cretaceous sequence drilled in the Tail End Graben, have led to the identification of possible submarine fan deposits in the lower part of the sequence. In the V-1 well, for example, interbedded sheet-like sandstones and siltstones of Late Ryazanian to early Valanginian age are interpreted as having been deposited from density currents by Hansen and Buch(1982). This sequence has a lobate, progradational expression on seismic data (Enclosure 16), with the source area located at the

intersection of the Adda Transverse Zone and the Coffee Soil Fault (figure 2.43). The Ryazanian/Valanginian age of this sequence predates the earliest onlapping unit in the E-1 well, which suggests that the fan systems prograding in to deep water from the fault scarps persisted from the Late Jurassic to the beginning of the Early Cretaceous, but died out at approximately the same time as the onlap fill commenced.

The upward transition from the early coarse, high energy fan systems of the fault scarps, to the more distal, low energy parallel and continuous onlap fill systems with their admixtures of fine grained turbidites and pelagic marls and limestones, and finally to the almost completely pelagic sequences of the Aptian and Albian is viewed here as signifying an overall upward decrease in the basin energy. This is explained as the natural consequence of a reduction in the basin floor relief during the progressive filling of the post-rift topographic depressions. As the topography became less pronounced, slope gradients dimished, and the potential energy necessary to stimulate and maintain gravity flow processes fell below critical values. In addition, the Apto-Albian sea level rise (Vail and Todd, 1981) drowned the flanking shelves as a prelude to the Late Cretaceous transgression, and the supply of clastics became dramatically reduced. The combination of high absolute sea level and reduction in topography heralded the change to widespread carbonate deposition.

In conclusion, the following important points are emphasised:-

(1) The major rift phase in the Danish Central Graben ended at the very latest at the beginning of the Hauterivian.

(2) The acceleration of the basement fault displacement in the Late Jurassic led to an outpacing of the sediment supply by the fault controlled subsidence, and this resulted in an accentuation of the

topography across the faulted margins. This pronounced topography stimulated the development of Late Jurassic and Early Cretaceous scarp-related fan systems, which acted to reduce the relief across the fault scarps. The short headed fan systems became inactive at the end of the Valanginian, and thereafter, axially transported distal turbiditic units onlapped the abandonded scarp aprons.

(3) The stratigraphic significance of the Base Cretaceous sequence boundary is highly variable. The relative importance of tectonic and eustatic signatures in the sequence boundary depends on the bathymetry and the local tectonic parameters of a particular area. The bathymetry was largely a function of structurally controlled subsidence patterns, but small fluctuations in absolute sea level were recorded even in the deep marine sequences, as variations in the proportions of pelagic and non-pelagic sediments, and in variations in the organic productivity.

CHAPTER THREE STRUCTURE.

3.1 INTRODUCTION.

The objectives of this chapter are:-

(1) To describe the major bounding faults of the Feda and Tail End Grabens, the associated fault systems within the grabens, and the structures on the flanking structural highs.

(2) To undertake a kinematic analysis of the extensional phase of development of the Danish Central Graben. The Late Cretaceous compressional phase of basin development has been considered in detail elsewhere (Vejbaek, 1987; Cartwright,1988a), and is therefore only briefly discussed in this chapter.

(3) To assess the relationship between sedimentation and tectonics in this rift setting by the extraction of structural information from the seismic stratigraphy.

The structure of the Danish Central Graben is of particular interest in that it marks the confluence of two variably oriented elements of the North Sea Rift (figure 1.2). Similar kinked rift trajectories are known from many other continental rifts, but no general explanation of this phenomenon has been established (Cartwright, 1988b). The lack of understanding is mainly through want of detailed structural analyses of the complex zones of deformation that characterise the major re-arrangements in rift orientation. A subsidiary aim of this chapter, therefore, is to lay a descriptive base for a later analysis of the origins of transverse segmentation in the North Sea Rift (Chapter 5).

In recent years, there has been a resurgence of interest in problems of extensional tectonics. This has stemmed from advances in

conventional and deep reflection seismic profiling. A variety of geometric models of extensional structures have been developed from the integration of field-geological studies and seismic data from active extensional provinces such as the Aegean Sea (Jackson and McKenzie, 1983), the Basin and Range Province (Wernicke and Burchfiel,1982), and ancient rifts or passive margin settings (Gibbs,1984; Le Pichon and Sibuet,1981). These essentially two-dimensional models have been widely applied in the interpretation of seismic and field data, but as yet, there have been very few detailed three-dimensional studies of the structure of extensional provinces which are suitable for the testing of these models. The underlying intention of this descriptive section of the thesis, therefore, is to provide just such a three-dimensional picture of the structure of a major rift, so that model making can at least in part be balanced by a measure of geological reality.

3.2 THE TAIL END GRABEN.

The Tail End Graben (TEG), is the northward continuation of the N-S trending Dutch Central Graben (figure 1.3). It is bounded to the east by the large basement structure, the Coffee Soil Fault(CSF), and to the west by a complex alignment of faults and minor folds termed here the Jens-Otto Fault Zone (JOFZ). The following sections document the main structural elements of the TEG, with particular emphasis on the kinematic significance of the structures and their stratigraphic setting.

3.2.1. The Coffee Soil Fault: Seismic Interpretation.

The shallow tip of the fault is easily identified on the seismic data either from the occurrence of a post-extensional monocline resulting from differential compaction of the hanging wall and footwall (e.g figures 3.12, 3.17), or from the occurrence of thrust out limbs of asymmetric folds formed during the Late Cretaceous basin inversion (e.g Enclosure 15).

The interpretation of the fault plane becomes progressively more complicated with depth. The footwall is composed primarily of crystalline basement rocks, and these give rise to a chaotic reflection signature. However, the stratal configurations in the hanging wall are generally continuous, so the fault plane can be interpreted from bedding terminations. In some areas, the Upper Jurassic sequence in the hanging wall is developed in a more discontinuous seismic facies, which reduces the contrast in reflection signature of the footwall and hanging wall and makes the interpretation of the shallow structural geometry less certain (e.g SP 10-14 on Enclosure 21).

Fault plane reflections are occasionally imaged, particularly where the lines are oriented for optimum migration, and, when present, they provide valuable additional constraints on the geometry. The strongest and most continuous fault plane reflections are observed in the deeper parts of the record sections (e.g figures 2.9 and 2.25), presumably as a result of the shallowing of fault plane inclination with depth. Complex ray paths and laterally varying velocity fields make accurate migration of these fault plane reflections difficult, and deeper stratal reflections are often observed to overlap the fault plane reflections (figure 2.9). Where overlap is observed, the fault plane reflection is

only used as a guide for the geometrical interpretation, and the true position of the fault plane is estimated from the envelope containing the majority of the stratal terminations.

Multiples generated between the top and base of the high velocity Chalk sequence and the sea bottom commonly interfere with genuine sratal terminations against the fault plane (Enclosure 15), and must be accounted for in the deeper positioning of the fault. These multiples are invariably overmigrated at the ends because of their low apparent velocity at great depth, and the migration smiles obscure the fault geometry. In spite of these problems a reasonable interpretation of the fault geometry is possible on most of the available seismic data, by combining the envelopes of stratal terminations with any fault plane reflections and making allowances for migration artefacts (Enclosure 21).

3.2.2 Geometry of the Coffee Soil Fault.

In previous accounts of the structure of the Danish Central Graben, the CSF has been mapped from relatively coarse seismic grids as a single curvilinear fault trace (Michelsen and Andersen,1983; Gowers and Saeboe,1985). Mapping of the upper tip of the fault scarp, using a much tighter grid shows, however, that whilst the fault is superficially curvilinear, in detail it is composed of several linear strike segments (Enclosure 21). This segmented geometry is also apparent at depth along the fault, as evidenced by the mapped positions of successive footwall cut-offs of the major Mesozoic sequence boundaries (Enclosure 21). Within each strike segment there is a uniformity of structural style on the seismic data, and the fault plane can be correlated with ease from section to section. At various points along the course of the fault, however, there are abrupt changes in orientation and sometimes in

inclination, often over short distances along strike. The positions of strike re-alignment are zones of considerable structural complexity (see section 3.2.4).

The segment of the CSF bounding the Sogne Basin has a N-S trend (Enclosures 2 and 3 , figure 1.3). The fault is planar at depth, dipping west at between 30 and 40 degrees, but steepening in the uppermost kilometre to a dip of approximately 60 degrees, giving a superficially listric geometry in cross section (Enclosure 22). The steepening upwards profile is attributed to the effects of propagation towards the free surface (Barnett et al.,1987), where stress conditions are more likely to conform to those predicted by Anderson (1951) for the development of high-angle normal faults. The fault is sharply resolved to the limits of the 6.5 second record length (Enclosure 12), and the planar geometry at depth is constrained by bedding terminations and a strong fault plane reflection (figure 2.25). Curvature of the fault plane reflection evident beneath the Base Zechstein on figure 2.25, is related however, not to a listric fault geometry, but to a significant increase in interval velocities on passing from the shales of the Triassic Bacton Group into the evaporites and tight clastics of the Upper and Lower Permian. Depth conversion reduces this curvature to zero (Enclosure 22).

At the boundary with the Northern Tail End Graben, the fault changes to a NNW-SSE strike, but the overall geometry is similar to that observed further north (Enclosure 13). The change of strike occurs over a distance of approximately ten kilometres, and in this interval there is evidence of considerable disruption of the integrity of the fault surface (SP 10-14 on Enclosure 21). Thereafter, the fault is recognisable as a tightly constrained envelope of bedding terminations

in a fairly simple arrangement (SP 16-30). In the vicinity of the V-1 and Per-1 wells (Enclosures 2 and 3), the strike changes abruptly to WNW-ESE. The fault is steeper along this obliquely oriented segment, and the level of associated deformation is far higher(SP 34) than that observed on those segments oriented parallel to the rift.

Several kilometres south of Per-1x (Enclosures 2 and 3), the fault resumes its more typical planar geometry and NNW-SSE strike (Enclosure 21). There is a poorly defined change to a NNE-SSW strike at the boundary of the Central and Southern Tail End Graben segments, and this appears to correspond to the development of a splay to the main fault plane (Enclosure 22, footwall cut-off at Base Zechstein). The fault is often poorly resolved at shallow structural levels as a result of complex detachment faulting associated with halokinesis of the thick Zechstein evaporites (Enclosure 19, figure 2.9). The complexity of the overburden geometry immediately above the presumed trace of the fault distorts normal incidence ray paths and makes a proper migration difficult. Numerous deep shallow dipping events appear to be 'stranded' within the footwall at several positions along the southern segment, but their planar configuration and continuity argues against their being overmigration artefacts. Instead, the deep terrace structure observed on lines SP 38, 40 and 44(Enclosure 21), is interpreted as a fragment of the early hanging wall left attached to the footwall by the adoption of the shallower dipping splay fault.

The relatively moderate Mesozoic displacement on the CSF in this southern part of the TEG permits a closer inspection of the early history of motion than is possible in the deeply subsiding areas further north. A strong fault plane reflection is apparent beneath the Mesozoic

cover on line SP 42(figure 2.9), and this is imaged to the bottom of the record section. It is convex upward in shape, but the convexity occurs directly beneath a large anticline in the Triassic and Jurassic sequences, and from the depth conversion it is clear that the curvature is related to a velocity pull-up (Enclosure 22). This line is important in that it demonstrates a consistent low-angle planar geometry for both the Upper Palaeozoic and the Mesozoic sections of the fault plane.

The documentation above of a fundamentally planar fault geometry along all the rift-parallel segments of the CSF, with dips in the range 30-40 degrees, is suggestive of some form of inheritance of pre-existing basement structure in the initiation and propogation of the CSF. The question of basement inheritance and non-Andersonian inclination of the CSF is addressed in Chapter 5, in a discussion of the deep structure of the rift.

3.2.3 Stratal Geometries, Graben Subsidence and Fault Displacement.

The segmented geometry of the CSF is not only manifested in the mapped configurations of the principal sequence boundaries, but also in the fundamental stratigraphic characteristics of the Tail End Graben. In the previous chapter it was argued from seismic-stratigraphic analysis of the graben fill sequences that sedimentation rates generally matched subsidence rates throughout the Triassic and Jurassic phases of basin development. In general, therefore, the gross reflection configurations can be directly equated to variations in the subsidence patterns, which in the case of the TEG were directly controlled by the activity of the CSF.

(1) The Sogne Basin Segment.

The pre-Cretaceous sequence has a grossly parallel reflection configuration. This is interpreted as having resulted from a horizontal

subsidence of the graben floor from the Late Permian to the Late Jurassic. Minor thinning is apparent in the Middle and Upper Jurassic sequences towards the Mandal High, but the degree to which the early horizontal subsidence altered to a more rotational form in the Late Jurassic is obscured by later truncation of the apex of the rotated fault block (Enclosure 12, figure 2.25). The truncation geometry at the Base Cretaceous unconformity over the western flank of the Sogne Basin, and the occurrence of mounded progradational configurations in the Late Jurassic adjacent to the CSF, suggest that the 10-15 degree tilt occurred during the Late Jurassic and Early Cretaceous.

The continuity of the rotated flank is broken by only a single major structure, the Lulu Fault, which bisects the Sogne Basin between the Mandal Fault and the CSF (Enclosure 2). The Lulu Fault probably originated as an antithetic fault to the CSF. The sense of displacement on the fault at Triassic and Jurassic structural levels varies along strike, which is suggestive of a scissors-type motion. It is difficult to constrain the early motion history of the fault, because of the complicating effects of halokinesis and Late Cretaceous inversion.

(2) The Northern Tail End Graben (NTEG).

The reflection configurations of the NTEG contrast markedly with those of the Sogne Basin. The Triassic sequence is similar in thickness and parallel configuration in both graben segments (Enclosures 7 and 21), and the two graben segments may have subsided as a contiguous body. However, the Jurassic sequence is considerably thicker in the NTEG and is characterised by highly divergent reflection configurations (Enclosures 8, 9, 13, 14 and 21). The divergence resulted from the rotational subsidence of the graben floor towards the CSF. This pattern was established to a limited extent at the beginning of the Bajocian,

but a rapid increase in the degree of divergence occurred in the early Oxfordian (Enclosure 13), and this more strongly asymmetric form of subsidence persisted until the end of the Jurassic.

The simple overall half-graben geometry of the NTEG is disrupted by a NNW trending pop-up structure which has outward facing bounding faults with reverse components at shallow structural levels (Enclosures 3,4, and 13). The bounding faults narrow at depth into a sub-vertical 'root' fault, and the combined geometry is typical of a flower structure (Harding,1985). The faults terminate upwards at the Base Cretaceous, but thinning of the Lower Cretaceous over the pop-up fold (Enclosures 10, 13) indicates that compressional deformation continued on from the Late Jurassic to the Early Cretaceous (Vejbaek, 1986). At deep structural levels, the structure is mapped as a splay off the CSF, continuing obliquely across the graben flank and intersecting the Lulu Transverse Zone (Enclosure 2). The variation along strike in displacement sense and style on the pop-up faults is suggestive of a history of oblique convergent motion across the structure.

(3) Central Tail End Graben (CTEG).

Isochore data show the thickness distribution and subsidence pattern of the CTEG to be extremely complex. Maximum depocentres shifted their position at different stages depending on the relative importance of the interacting basement faults. An additional complicating factor was the offset of the CSF along the Adda Transverse Zone. In the Triassic and Middle Jurassic, both the CSF and the Gorm Fault Zone (section 3.2.6) were active in controlling subsidence of the graben floor (figure 3.3). This is expressed in divergent reflection configurations for these sequences (Enclosure 15) and in asymmetrically disposed isochore maxima (Enclosures 7 and 8). Small high frequency isochore anomalies mapped

adjacent to the Adda Transverse Zone are attributed to complex strains associated with oblique slip along the dog-leg segment of the CSF (see section 3.2.4). Active faulting along the Gorm Fault Zone ceased at the beginning of the Late Jurassic, and a single large depocentre was established over the trace of the fault scarp. The Oxfordian and Kimmeridgian sequences diverge towards the CSF (Enclosures 15 and 16), implying a continuation of rotational subsidence into the Late Jurassic, but the Volgian sequence converges towards the CSF, signifying that large scale displacement on the CSF had come to an end (Enclosure 9).

(4) Southern Tail End Graben (STEG).

The reflection configurations of the Triassic and Jurassic are grossly parallel, when local thickness variation due to halokinesis is taken perterbed on a local scale by thickness variations associated with halokinesis (e.g. Enclosures 18 and 19). The rapid thickening towards the CSF indicated for the Triassic on enclosure 7, for example, is attributed to duplication of the sequence by complex detachment faulting, and by the formation of rim synclines (figure 3.10). The floor of the graben is near horizontal, and from this observation and the parallelism of the stratal configurations, it is concluded that the STEG subsided horizontally throughout the Triassic and the Jurassic.

In summary, the four segments of the Tail End Graben corresponding to the four rift-parallel strike elements of the CSF, exhibit marked variations in the timing, style and magnitude of their Mesozoic subsidence. These variations are an expression of the along strike variation in the displacement characteristics of the major controlling basement fault (figure 3.1). The Sogne Basin and STEG segments subsided horizontally for a large part of the Triassic and Jurassic, and the magnitude of the Jurassic subsidence was considerably less than in

either the CTEG or the NTEG. The NTEG and the CTEG exhibit a strongly asymmetric rotational form of graben subsidence, but the transition from the earlier horizontal pattern occurred at different times in the two segments. The changes in style and magnitude carry with them an implication of relative torsional motions between the variably subsiding blocks. The following section describes the structure of the segment boundaries to examine whether the observed deformation is compatible with that to be expected from the longitudinal variation in subsidence style.

3.2.4 Transverse Fault Zones.

The segmentation of the Tail End Graben has been described in terms of the geometry of the CSF. It is apparent, however, from structural and isochore mapping, that this subdivision is not solely restricted to the near-field deformation associated with longitudinal variation in displacement on the CSF. Maps of all the Mesozoic sequences show a strong alignment of faults, minor fold patterns, and steep isochore gradients, in three fairly broad zones oriented transversely with respect to the graben axis, connecting offsets or changes of strike of both the graben margins (figure 1.3). These linear zones are regarded as the structural boundaries of the four graben segments. Their presence is intimately linked to the capacity of the graben segments to subside differentially. The structure and seismic expression of the segment boundaries is described in this section, and their kinematic significance in the wider context of the evolution of the rift is discussed in Chapter 5.

(1) The Lulu Transverse Zone.

The Lulu Transverse Zone is a complex intersection of several fault trends, which coincides with a major stratigraphic hinge at the

junction of the Sogne Basin and the NTEG (Enclosures 2 and 3). The Middle and Upper Jurassic sequences thin abruptly northward towards the hinge, and this is expressed on the isochore maps as a broad WNW trending alignment of contours linking the Mandal Fault and the kink in strike of the CSF (Enclosures 8 and 9). The pronounced WNW trend of the hinge is also seen in the pinch-out of the Lower Cretaceous and a steep contour gradient in the Upper Cretaceous isochore (Enclosures 10 and 11).

The deep structure of the Lulu Transverse Zone is poorly resolved on the seismic data (Enclosure 18). The oblique intersection of the dip and strike lines with the main faults prevents a full migration, and migration smiles and chalk multiples impair the data quality. The strike lines provide the clearest indication of the deeper structure. On lines SP 27 and 29, for example (Enclosure 18, figure 3.2), a broad zone of fracturing affecting the Jurassic and Triassic sequences coincides with the locus of maximum thinning of the Jurassic and Lower Cretaceous sequences. Individual vertical and sub-vertical faults can be identified from stratal offsets, but closer to the CSF, the level of deformation increases, and entire sections of the hanging wall are pervasively fractured to the extent that all bedding plane reflection coherence is lost. Low-angle fault plane reflections observed on strike lines (e.g Enclosure 18) are found from correlation with the intersecting dip lines to be out-of-plane strike sections of steeper faults (see Chapter 1.6).

Correlation of faults from section to section along the zone is difficult, but there is sufficient control to establish that there are rapid lateral variations in displacement on some of the largest faults in the zone. The largest of the component faults of the Lulu Transverse

Zone is the Mandal Fault (figure 1.3). The displacement on the fault decreases eastwards as it enters the Tail End Graben from its position bordering the Feda Graben (Enclosure 8). Anomalous stratal configurations in the hanging wall of the Tail End Graben immediately adjacent to the CSF on lines SP 10, 12, and 14 (Enclosure 21), are interpreted as resulting from a fragmentation of the CSF at the position of strike re-arrangement. This position is at the projected intersection of the Mandal Fault and the CSF. On the strike line immediately adjacent to the CSF across this projected intersection (figure 3.3), a series of faults and folds in the Jurassic and Triassic can be seen to coincide with a zone of rapid lateral offsets in the dip line intercepts of the CSF (figure 3.3). The magnitude of the vertical separation of the successive fault plane intercepts is such that the only possible interpretation is that the CSF and the footwall (the Ringkobing-Fyn High) are transected by the component faults of the Lulu Transverse Zone i.e the Mandal Fault. The faulted and folded cover sequences (Triassic and Jurassic) along the segment boundary represent the shallow expression of basement deformation along the Mandal Fault. It has not been possible to trace the Mandal Fault or any related structure for any distance into the Ringkobing-Fyn High. There is no indication of faulting at the Mesozoic surface over the area adjacent to the last mapped position of the transverse zone, and the resolution of the basement lithologies is insufficient to allow any structures to be mapped.

The pattern of deformation along the Lulu Transverse Zone, with the dominance of deep basement faults, rapid lateral variation in displacement, and often pervasive shattering of the pre-Cretaceous cover sequences is suggestive of a complex torsional displacement of the NTEG

relative to the Sogne Basin, superimposed over net downward relative displacement of the NTEG. The largest offsets are expressed at Jurassic structural levels, and this is consistent with the preceding description of the relative subsidence histories of the two graben segments (section 3.2.3). The similarity in gross thicknesses of the Triassic in the two segments implies that the two graben segments subsided in tandem, and as such there was no requirement for any relative motion to be expressed along the segment boundary. This same condition also applied during the Middle Jurassic, but the onset of the accelerated phase of extension and subsidence in the Late Jurassic, saw the adjoining segments react in strongly contrasting ways, with the NTEG subsiding asymmetrically, and the Sogne Basin subsiding horizontally at a much slower rate (figure 2.30). The difference in the rate of slip on the two segments of the CSF (figure 3.1) automatically introduced a condition of relative motion along the segment boundary. The torsional motion on the segment boundary reactivated the WNW trending basement lineament represented in part by the Mandal Fault, and a zone of fracturing propagated in the cover sequence above the trace of the basement dislocation. This zone extended south-eastwards from the rapidly subsiding Feda Graben and penetrated into the footwall of the Ringkobing-Fyn High.

The rapid decrease of displacement along the Mandal Fault towards its projected intersection with the CSF suggests, however, that there was no simple and direct transfer of slip at this triple fault intersection as has been suggested in recent geometrical models of this type of structural setting (Gibbs, 1984; Etheridge, 1986). The large rotational component of the NTEG would in that case have led to an increase in the normal component of displacement across the segment

boundary towards the locus of maximum differential displacement immediately adjacent to the CSF. The observation of penetrative deformation of the footwall at the zone of strike re-arrangement, together with the complex means by which the torsion between the differentially subsiding graben segments was disseminated through the hanging wall is perhaps suggestive of a complex three-dimensional jostling of the graben segments whereby a limited amount of differential rotation about a vertical axis between the two segments accompanied the more obvious rotations about a horizontal axis.

(2) The Adda Transverse Zone.

The Adda Transverse Zone is a complex arrangement of structures along a broad transect separating the NTEG and the CTEG, with the plan-view appearance of a graben dog-leg(Harding,1984). Both margins are displaced in an apparent sinistral sense across the boundary, but the normal components of the two offset margin faults are in opposite senses(Enclosures 2 and 3). The dog-leg margins are connected by a discontinuous alignment of minor faults affecting Jurassic and older strata, but the observed level of deformation in the axial portion of the zone is far smaller than that described from the Lulu Transverse Zone. There is certainly no indication of the intense fracturing that would be expected from a major wrench structure. It is concluded, therefore, that the dog-leg pattern is a feature inherited prior to the onset of motion on the CSF in the Westphalian, and the sinistral shift of the NNW striking segments of the CSF does not represent a lateral displacement of the northern part of the graben relative to the south. The co-linear arrangement of the two offset margins suggests that a WNW-ESE trending basement fracture is present at depth linking the two margins, but is only weakly expressed as the discontinuous fault zone in the cover. The great depths of burial of the axial part of the graben

prevent any direct observation of such a basement fault on the seismic data (Enclosure 18), but the mapping of a suite of basement faults with the same trend along the nearby Olaf Fault Zone lends further support to this supposition (see section 3.6).

The peculiar geometry of the dog-leg portion of the CSF evidently resulted in serious difficulties for a smooth distribution of displacement along the CSF. These difficulties were partially alleviated by the transfer of displacement on to the Gorm Fault Zone (figure 3.3). As with the Lulu Transverse Zone, the similarity of thickness of the Triassic on either side of the Adda Transverse Zone implies that the adjoining graben segments (the NTEG and the CTEG) subsided in tandem. The Gorm Fault was probably a southerly continuation of the CSF, and the integrity of the combined fault surfaces was maintained until the Late Jurassic. When the two segments began to subside diferentially in the Callovian/Oxfordian, the connection was breached, and a new linkage of active fractures became established along the dog-legged margin. The Gorm Fault ceased to be active as a locus for rotational subsidence, and the Adda Transverse Zone propagated in its place. This new arrangement created a triangular-shaped block in the corner of the dog-leg, and judging from the intensly fractured appearance of this block on the seismic data (Enclosures 16 and 19), and from the rapidly changing isochore values (Enclosures 8 and 9), the difficulties encountered in maintaining an kinematically viable system with the dog-leg geometry of the fault plane were not completely overcome. Any deviation from a pure dip-slip regime would, under these geometric constraints, be expected to produce frictional deformation effects along the irregular margins. The subsequent confinement of active displacement on the CSF to the NTEG may in part be attributed to the 'blocking' effect of the buttress of the

dog-leg to smooth fault propagation towards the south. The intense fracturing in the 'lee' of the Adda dog-leg, may thus be understood as the result of a re-ordering of slip vectors on the CSF, and the concomitant focussing of slip into the central portion of the fault (figure 3.1).

Along the dog-leg portion of the segment boundary, the zone of deformation is approximately 15km wide, and large offsets on deeper faults are observed to pass upwards into sub-vertical tranches where all reflection continuity is lost (Enclosure 19). This loss of reflectivity is comparable to that seen on figure 3.2, and is thought to be a genuine response to the intense level of the deformation rather than an artefact of the acquisition or the processing of the seismic data. In comparison, the degree of faulting in the axial portion of the zone is trivial (Enclosure 18). Most of the localised fracturing in this axial portion occurred during the Volgian, but larger faults at depth were active earlier, and may link in turn to basement structures beneath the floor of the graben. The decrease in the intensity of the reactivation of the presumed basement dislocation from the eastern margin towards the graben axis may be explained by a 'spilling' of part of the torsional motion along the segment segment boundary on to the Gorm Fault. Such a mechanism might also account for the scissors component of the Gorm Fault at Upper Jurassic levels (see section 3.2.6).

The complexity of the Jurassic isochore patterns in the vicinity of the segment boundary reflects the variation in the influence of the Gorm Fault, and the change in displacement around the dog-leg of the CSF. Small elliptical depocentres cluster at the tips of the major interacting faults, possibly indicating a ductile response in the shale dominated cover sequences to the relative motions prescribed by the

bounding structures. The intense deformation of the triangular corner block does not seem wholly consistent with the simple oblique extension demanded by the differential rotations on the two adjacent, offset rift-parallel segments of the CSF. The large northward rotation of the eastern side of the CTEG during the Callovian-Kimmeridgian (Enclosure 19) may have been achieved by increments of both normal and oblique slip along both the bounding margins of the dog-leg. Minor reactivation of the controlling basement elements during the Early and Late Cretaceous can be seen from transverse alignments of tightly bunched contours in their isochore patterns (Enclosures 10 and 11).

(3) The Dan Transverse Zone.

The Dan Transverse Zone is a WNW trending discontinuous alignment of minor faults expressed at a variety of structural levels which coincides with a break of slope of the graben floor from the STEG to the CTEG (Enclosure 18). On the eastern margin, the zone projects directly into the position of strike re-arrangement of the CSF. The structure of the CSF in the vicinity of the intersection is poorly defined because of the wide grid spacing in this area (figure 1.1). However, there is some evidence to suggest that the change of strike occurs at a position where two en echelon strands of the CSF overlap (section 3.2.2). The possibility of a genetic relationship between fault splaying or bifurcation and the development of transverse structures is considered further in Chapter 5.

The pronounced WNW trend of the zone is apparent in the isochore data for the post-Triassic sequences as a linear set of bunched contours (Enclosures 9-11). In cross-section this isochore gradient is manifested as a stratigraphic hinge zone (Chapter 2.6) similar to those forming the western and northern margins of the deep Jurassic basin. The

Bajocian-Kimmeridgian sequences can be seen, for example, to thicken rapidly across a deeper break of slope towards the CTEG (Enclosure 19), and from the progradational reflection configurations, it is clear that the shelf-slope break was influenced by the deeper hinge-type structure of the segment boundary (figure 2.35). The monoclinal structure of the hinge is dissected by suites of crestal collapse faults with minor displacements, that sole into underlying Triassic or Zechstein evaporite horizons (Enclosure 18). On the strike seismic sections, there is evidence of deeper faulting at the core of the hinge affecting the pre-Zechstein sedimentary sequences. It is not known whether these deeper faults continue into the crystalline basement at depth, but given the thickness of the Upper Palaeozoic cover, it seems unlikely that motion on any basement faults would have been translated directly into the Mesozoic sequences, unless the magnitude of the displacement was very large. Minor displacements of the basement rocks flooring the graben may very easily have been taken up by ductile deformation of the thick Upper Palaeozoic sequence or the mobile Zechstein evaporites. The thicknesses of the Triassic and Jurassic sequences on either side of the segment boundary are comparable, and only minor torsional relative displacements of the neighbouring segments are likely to have occurred. Nevertheless, the preferred WNW trending alignment of the minor fracture pattern again argues for some form of basement control on the later structural and stratigraphic development. The intervening buttress of the thick Upper Palaeozoic sequences and the potential for the decoupling of the cover at the various evaporite layers may plausibly account for the diffuse pattern of deformation observed above the presumed trace of the basement structure forming the deeper part of the segment boundary (figure 3.4).

The three transverse fault zones described above exhibit a range of structural and stratigraphic styles. Several general points can, however, be drawn from the description and comparison of these three examples:-

(1) The transverse zones are a fundamental expression of the segmentation of the Tail End Graben. They link margin to margin, and in all three cases continue either into one or both of the adjoining structural highs, or into another zone of basement dislocation.

(2) The deformation along the zones occurred during the Late Jurassic at a time of rapid rotational subsidence in the central segments and pronounced torsion between adjacent, differentially subsiding segments. The possibility of earlier, minor movements can not, however, be excluded. The intensity and distribution of the deformation depends on the configuration of the conjugate margins, the availability and relative orientations of deep-seated fracture surfaces, and the presence or absence of a lubricant in the cover sequence.

(3) The discontinuity of the component faults within the cover argues against any significant horizontal translation along the transverse zones, although locally, the intensity of the pervasive minor fracturing suggests fairly complex oblique paths of motion. The sense of differential motion between adjoining segments predicted from comparisons of the sense and amount of subsidence of each segment, is generally compatible with the overall style of deformation on the zones. The final observed structure is, however, the product of several contrasting slip phases, and when these involve oblique components, the variation in sediment thickness across structures within the transverse zones can not be used in a direct way to quantify the relative slip vector of adjoining graben segments.

(4) The three transverse zones all have a marked WNW-ESE trend. In the case of the Lulu Transverse Zone, this is clearly related to the presence of a large basement fault transecting the graben. Although direct observation of the deep structure is lacking in the other two examples, the persistent adoption of the trend is strongly suggestive of basement control on the overall fracture pattern. The nature of this postulated basement control is discussed in Chapter 5.

(5) The transverse zones exerted a profound influence on the rift depositional systems during both the extensional and compressional phases of basin development. In their role as boundaries between differentially subsiding segments, they controlled the morphology of the depositional surface, exemplified by the positioning of the Late Jurassic shelf edges (figure 2.30). The intersection of the transverse zones with the margin structures created topographic features which formed loci for the transport of erosion products from the shoulders into the axis of the graben (figure 2.43).

3.2.5 The Jens-Otto Fault Zone (JOFZ).

The JOFZ forms the western margin of the Tail End Graben. It is composed of several strike elements and has a segmented structure in accordance with that of the rest of the graben. The various elements range in strike from N-S to WNW-ESE, but overall the trend is NNW-SSE (Enclosures 2, 3, and 23; figure 1.3).

The deep structure is composed of a single 'root' fault, which forms a foundation for the shallower structure. The progressive development of the structure can be explained by reference to the inclination and polarity of the root fault. From north to south, the panel of cross-sectional line drawings (Enclosure 23) shows a change from a west-dipping polarity(SP-12), through a sub-vertical symmetric

form (SP14-18), to an east-dipping polarity (SP 20-30), and finally back to a west-dipping polarity (SP32, DCS107). In addition, the magnitude of displacement of deep structural markers changes across the root fault abruptly when there is a change in polarity, but changes more gradually and systematically along any given strike segment. Note, for example, the progressive increase in the Jurassic offsets across the root fault from SP18 to SP26. Structural maps of the deeper marker horizons show that these relatively abrupt changes in the deep structure either in polarity or in the sense of displacement all coincide with the intersections of the transverse fault zones forming the segment boundaries in the graben (Enclosures 1,2 and 3).

A variety of minor faults both antithetic and synthetic to the root structure are apparent on Enclosure 23. They are arranged in a V-shaped pattern, narrowing onto the root fault near the base of the graben fill. This pattern is reminiscent of that described from crestal collapse structures formed over the crests of syn-depositional folds in areas of salt tectonics or deltaic growth faulting (Fallaw,1973, Gussow,1968). The crestal faults of the JOFZ are syn-depositional, and growth components are evident on the isochore maps (Enclosures 9 and 10) and the cross-sections (Enclosure 23).

The crestal faulting at shallow structural levels is superposed over a monoclinal hinge, similar in cross-sectional appearance to the hinges along the Lulu and Dan Transverse Zones (section 3.2.4). The Jurassic and Lower Cretaceous sequences thin rapidly across the hinge, and there are several unconformities of local extent developed within the rapidly condensing sequences (Enclosure 14 and 15). The largest growth indices on the crestal faults are mapped at Upper Jurassic

levels, signifying that the faults were most active during the period of most rapid stratal divergence on the adjacent rotating graben flank. This suggests that fault development over the hinge was genetically related to the motion on the CSF. The simplest kinematic interpretation of the crestal fault pattern is that it developed in response to stretching over the rotational hinge. The JOFZ was in effect acting as a fulcrum for the rotation of the graben floor towards the CSF. The rapid thickness variations observed along the strike of the zone (Enclosure 23) can be accounted for by this mechanism of syn-depositional crestal fault growth.

An additional factor in the development of the crestal fracture system which also contributed to the variation of thickness along strike was the presence of a fairly thick sequence of mobile Zechstein evaporites. The mobile evaporites may have acted as a lubricating agent, allowing the easier propagation of the crestal conjugate collapse fault system. Local space problems are often created by synchronous activity on 'Y' or 'X' shaped fault networks in crestal collapse structures (Curray, 1956; Horsfield,1980), but in this case these space problems may have been alleviated by salt flowage. Salt diapirs occur along the northern part of the JOFZ (Enclosure 13) near a localised Early Cretaceous collapse graben (SP's 16 to 20), and although this abrupt thickening has been attributed to wrenching along the JOFZ (Vejbaek,1986), a simpler explanation of the thickness distribution is one involving salt withdrawal faulting.

The JOFZ was a major locus of compressional reactivation during the Late Cretaceous (Vejbaek and Andersen,1987; Cartwright,1988a). This compressional deformation is expressed as minor reverse reactivation of the larger component faults of the earlier crestal collapse structures,

a more limited propogation of new thrust faults, and the formation of pop-up folds of varying amplitude and vergence (Enclosure 23). The reverse components are in the range 100-300 metres, and because they are small, the reactivated faults retain a net normal sense of displacement.

In general, there is a dependent relationship between the vergence of the asymmetric Late Cretaceous growth folds and the polarity of inclination of the underlying root faults. Where the root fault is east-dipping, the fold verges to the west, and the outward facing limb is commonly thrust over the adjacent undeformed area (e.g SP's 22-26). This contrasts with west-dipping root faults, where the fold vergence is to the east e.g SP16). On the margin of the CTEG, the root fault is nearly vertical, possibly as a result of rotation of an earlier less steeply inclined fault into the vertical position as part of the more general rotation of the graben flank (figure 3.5). In this case, the Late Cretaceous fold is symmetrical, and forthrusts and backthrusts propagated from the antithetic and synthetic crestal normal faults (SP's 28 and 30).

The largest reverse components are observed at the Base Upper Cretaceous (Enclosure 5). There is an inverse relationship between the amplitude of the pop-up folds and the magnitude of the thrust components on the reactivated crestal faults. Compare, for example, SP 30 where there is a large fold amplitude and only minor thrust components, with SP 20, where the reverse applies. It is interesting to note that the largest fold amplitudes developed where the root fault was steepest. This suggests that shortening was most easily accomplished on sectors of the JOFZ with gently inclined root structures, where it was then expressed in fault reactivation without significant accompanying buckling. The steeply dipping root faults evidently represented an

obstacle to straightforward and energy-conserving fault plane reactivation, and the shortening was almost entirely expressed in tight buckling. An exception to this general rule can be seen on sections SP 32, and DCS 107 (Enclosure 23). in this part of the JOFZ, the asymmetric thrust/fold pair verges to the west, but the root fault dips to the east (figure 3.6). The shortening thus appears to have gone against the grain of the obvious mechanical anisotropy. Why is this so? The answer here lies in the Zechstein salt pillow which straddles the root fault (Enclosure 15). The inclined sequence of Zechstein evaporites draped on the graben floor would have been in an ideal position to function as a décollement horizon, and the pillow would perhaps have nullified the mechanical contrast of the stepped morphology of the graben floor across the root fault. Under these dual circumstances, the propagation of a listric thrust climbing up from the Zechstein décollement to the Late Cretaceous sea bottom is considered to have been preferred to the reactivation of the root fault.

The final geometry illustrated in the line drawing interpretations shows that where the hinge is tightly buckled, the crestal faults have strongly curved profiles (Enclosure 23). The implication of this is that the originally planar crestal faults were buckled along with their predominantly shaly (and possibly overpressured) matrix. It is also highly probable that continuous rotation of the outer parts of the hinge structure in concert with the rotation of the Tail End Graben led to the propagation of curved fault surfaces. Early formed steep faults would have been rotated to shallower inclinations, and these would have propagated upwards with steeper trajectories, giving a concave final geometry (figure 3.7). Subsequent folding of these initially curved

surfaces then produced the assortment of concave and convex upwards geometries portrayed on Enclosure 23.

A comparison of the structural maps of the JOFZ at levels representing the early extensional structure and the later compressional structure (figure 3.8) shows that the orientation and vergence of the Late Cretaceous thrusts and asymmetric folds was conditioned exclusively by the segmented arrangement of the extensional fault systems. The segmented form of the compressional structures mimics directly the form of the extensional structure. This correspondence is a further confirmation of the relatively simple kinematic evolution of the JOFZ. The complex structural geometries are envisaged here as the product of superimposing several distinct, though simple kinematic phases on the same fundamental fault structure.

A different view of the structural evolution stems from the consideration of certain fault geometries as being diagnostic of particular kinematic paths. In this case, the geometry in question is the Flower Structure (Harding, 1985). In cross section and in map view, the JOFZ exhibits many features which are usually regarded as diagnostic of Flower Structures. A root fault that dips steeply, passes upwards into branching outwards splay faults, to give a geometry resembling that produced in analogue models of wrench structures (Naylor et al.,1986). The rapid variations in the sense and amount of displacement along strike, and often abrupt variations in thickness of individual sequences across and along the structure are also cited in many instances as indicators of strike-slip motion (e.g Glennie,1986). The structural maps could be described as showing a crudely en echelon pattern, although as has been argued above, this is more a facet of the segmented extensional structure than any genuine shear fabric. Previous

accounts of the structural evolution of the JOFZ have argued that since the fault zone looks like a flower structure, and the faults are en echelon, then the deformation must have been produced by wrenching (Michelsen and Andersen,1983, Vejbaek,1986, Frandsen et al.,1987, and Vejbaek and Andersen,1987).

In contrast, the interpretation proposed here of a polyphase dip-slip kinematic evolution, stresses the role of the transverse segmentation of the Tail End Graben in controlling the detail of the structural geometry of the JOFZ. The steeply dipping root faults and the shallower splaying networks of antithetic and synthetic faults are interpreted as crestal collapse structures contingent upon the progressive rotation of the graben flank. Along-strike variation in the crestal collapse structure, in both the timing and magnitude of growth components is attributed to the differences in timing and sense of rotational subsidence of the various graben segments. The possible role of salt withdrawal and intrusion is also emphasised in accounting for rapid thickness variations (figure 3.9). The curved trajectories of many of the minor faults are explained by differential rotation at successive structural levels of the extensional hinge, and subsequent compressional tightening of the monoclinal fold and buckling of the fault planes in their ductile shaly matrix.

Perhaps the most conclusive argument against a wrench origin for the JOFZ lies in the preservation of the segmented disposition of the minor fault trends from the extensional to the compressive phases of structural development. The structural mapping shows that there is no inter-connecting network of faults at shallow structural levels, and offsets of Late Cretaceous reverse faults and fold axes are directly

superposed on offsets or tips of the deeper structures at the intersections with the transverse segment boundaries. The complex fault patterns observed at these nodal intersections (figure 3.8) are no more than should be expected at the confluence of two obliquely trending fault zones. In conclusion, the structure of the JOFZ can be explained by the superposition of several episodes of dominantly dip-slip motion, in extensional and compressive boundary conditions, coupled with plane strain rotations associated firstly with flank subsidence, and then later with compressional folding. The flower-type geometry of the JOFZ was accrued gradually through these successive phases rather than in a single wrench deformation. This conclusion highlights the danger in attaching a particular kinematic interpretation to a particular structural geometry. The structural evolution is summarised in figure 3.9.

3.2.6 The Gorm Fault Zone (GFZ).

The GFZ is a N-S trending alignment of faults and salt structures crossing the STEG and the CTEG, intersecting the CSF at its northern limit. There is a large offset of the Base Zechstein across the GFZ, with the relatively upthrown block on the eastern side (Enclosure 1). In the CTEG, this offset is seen to be associated with a large west-dipping normal fault, and divergent Triassic and Middle-early Upper Jurassic sequences expand towards the fault (Enclosure 15). The trace of this fault projects directly from the end of the CSF in the NTEG (Enclosure 1), and the similarity in Triassic thicknesses in the CTEG and NTEG (Enclosure 7) suggests that the Gorm Fault may have originally been contiguous with the northern sector of the CSF (figure 3.3). At shallower structural levels, however, the zone of pronounced activity becomes situated progressively further to the South (Enclosures 2 and

3). In the STEG, the fault pattern of the GFZ is more complex, and the thick Zechstein evaporites were a major controlling factor in the structural development. A tight anticlinal structure is associated with the fault zone, and although this is partly related to salt pillow formation, there is evidence of a compressional component in the formation of the anticline. On SP 38 (figure 3.10) for example, the large offset of the Base Zechstein can be seen to be related to a west-verging reverse fault, which dies out at the Base Volgian at the point of inflection of a large anticlinal limb. The deeper structure is obscured by migration smiles and loss of energy in the fault shadow zone, and it is not clear whether this thrust fault steepens or flattens at depth. The Upper Triassic sequence thickens towards the fault zone on the upthrown block, suggesting that the 'root' of this structure was a syn-depositional normal fault throwing down to the east. The Bajocian to Kimmeridgian sequence is thinner on the upthrown block, indicating that syn-depositional thrusting commenced during the Middle Jurassic, and continued into the Upper Jurassic (figure 3.11). Despite the fact that the Base Volgian is not offset by the thrust, the geometry of the Volgian sequence suggests that continued shortening was expressed in the form of the large growth anticline.

In conclusion, it is suggested that the GFZ formed as a co-linear arrangement of normal faults discontinuous during the Triassic, and was then reactivated during the Jurassic as a scissors structure, with continued normal faulting on the west-dipping basement fault in the CTEG, and thrust faulting with a westerly vergence on an earlier east-dipping fault surface in the STEG (figure 3.11).

3.3 PALINSPASTIC RESTORATION OF MOTION ON THE COFFEE SOIL FAULT.

3.3.1 Introduction.

This section documents an attempt to quantify the history and magnitude of displacement of the CSF, through the detailed reconstruction of a seismic cross section across the NTEG (figure 3.12). The section was chosen by virtue of its orthogonal position relative to the fault plane, and its location near the point of maximum displacement on the CSF where there are no complicating effects from Late Cretaceous reverse reactivation. The method is based on the fundamental principal that the reflection configurations in the hanging wall of any major basement normal fault are the product of three variables: (1)the fault controlled subsidence of the depositional surface, (2)the depositional systems (sediment supply characteristics), and (3)the absolute sea level. Changes in any of these variables can result in rise or fall of relative sea level (Vail et al.,1977), but if the order of magnitude of the changes in one of the variables is far greater than in the other two, it should be possible to extract the signature of that variable from the seismic-stratigraphic record.

Estimates of the amplitude of the absolute sea level changes during the Mesozoic range from 100-300 metres (Vail et al.,1977; Pitman,1978). Since the magnitude of these oscillations is small relative to the total vertical displacement represented by the fault-bounded fill of 6-8000 metres, variations in absolute sea level can be neglected without incurring significant errors.

The ubiquity of parallel and continuous reflection configurations in the Triassic and Jurassic sequences in the TEG suggests that sediment supply rates were approximately equal to the subsidence rate throughout

this interval. This balance between the rates of sediment supply and subsidence means that bedding plane reflections can be used as markers for the position of the depositional surface. By calibrating these reflections with the biostratigraphic zonations in nearby wells, a plot of the magnitude of the fault-controlled subsidence can be constructed from the seismic data simply by measuring the bed-normal thicknesses of known straigraphic intervals (the displacement index of figure 3.1).

Two important factors which must be taken into account before proceeding with the reconstruction. These are the effect of compaction, and the variation of bathymetry with time. In the case of the bathymetry, the reconstruction relies on the mainly qualitative assessment of the relief of the fault scarp. It is difficult to estimate the relief without the benefit of any well penetrations of the hanging wall immediately adjacent to the fault plane. On seismic-stratigraphic grounds, it is probable that the fault scarp was only a minor feature on the basin floor for most of the period under consideration. The hanging wall reflection configurations are, with the exception of the uppermost part of the sequence, parallel and continuous, and in no way suggestive of any significant topographic break of slope. By the late Volgian, however, there was considerable relief on the fault scarp, and the increased slope gradients were probably instrumental in stimulating the development of scarp-related submarine fan systems (Chapter 2.6 and 2.7). Since the depositional surface was an almost direct representation of the upper fault tip for most of the period of fault motion, the bathymetry is assumed to have been constant and the late increase can be neglected. The reconstruction does, however, provide an explanation for the increase in relief of the fault scarp (see below).

The sedimentary fill of the NTEG is almost entirely composed of fine grained clastic rocks, which are known to compact on burial to far greater extents than many other lithologies (Magara, 1976). Compaction of the thick sequences of Triassic and Jurassic shales would have modified the original depositional relationships, and the thicknesses of given units measured from the seismic data would no longer be a direct representation of the amount of fault controlled subsidence for that period. In order to obtain values for the original pre-compaction thicknesses, and hence the amount of basement subsidence, it is necessary to decompact the sedimentary fill of the hanging wall. This procedure has been applied mainly in the backstripping of wells and in the calculation of "tectonic subsidence" curves (Sclater and Christie, 1980; Barton and Wood,1984), but in the following section the established techniques of decompaction are employed in an adapted form in a two-dimensional palinspastic reconstruction. This adaptation is in a preliminary stage of development, but it was considered a significant enough improvement over reconstructions which were made without decompaction that it was decided to report the results of this work here.

3.3.2 Decompaction.

The technique used to decompact the cross section was modified from that described by Sclater and Christie (1980) by A.Price (unpublished manuscript, 1987). The two methods are illustrated schematically in figure 3.13. They produce similar results, but Price's approach is simpler to compute. Both these methods are liable to significant error when the thickness of a layer removed in a single iteration is large (greater than 500 metres). Units 500-2500m thick were removed in single stages and errors of between 100-500m are considered likely for the

absolute reconstructed thicknesses. These errors are large, but are nevertheless significantly smaller than the errors in the reconstructed position of the basement if compaction is ignored.

The decompaction assumed, for simplicity, that the Mesozoic and Cenozoic sequences are normally pressured. The Lower Tertiary and the Upper Cretaceous are both known to be overpressured (Michelsen,1982), but since both these sequences were deposited after active basement faulting had ceased, it is permissible to neglect the overpressures without introducing any errors in the decompaction of the syn-rift sequences. The effect of this simplification is that the decompaction overestimates the loss of thickness in the Upper Cretaceous interval. Sonic logs of the Upper Jurassic shaly sequences drilled in I-1 and E-1 (Michelsen and Andersen,1983) show a steady increase of velocity with depth, which suggests that the shales conform to a normal compaction gradient (Magara,1976). Well control of the variation of porosity with depth for the deeper parts of the Jurassic and Triassic intervals in the vicinity of the cross section are lacking. Velocity analysis of equivalent sequences drilled in the STEG suggests a fairly steady increase of density and therefore loss of porosity with depth, but it is not known whether the same conditions applied in the NTEG where the Late Jurassic rate of subsidence was much higher. In the absence of detailed sonic and density information from the vicinity of the section, it was decided to use the averaged North Sea porosity versus depth curves compiled by Sclater and Christie (1980).

Vertical columns were drawn at intervals of 2-4km across the line of section (figure 3.14), and thicknesses of the age calibrated sequences were measured directly from the depth converted seismic line (Enclosure 21). The lithologies assigned to each interval were

collated on an averaged basis from the closest well penetrations, and simplified to the extent that minor intercalations of subordinate lithologies were neglected.

The vertical columns were decompacted and successive cross sections were constructed for each of the pre-compaction intervals (figure 3.15). The construction assumed that the CSF did not itself rotate during the extension. The Dogger Platform was taken as a nominal pin line. Slip vectors of all points in the hanging wall were assumed to be parallel to the slip vector of the CSF. The slip vector of the CSF is not constrained, but for this calculation, it was assumed to be parallel to a line of maximum dip of the fault surface. In reality, the cumulative slip vector may have a complex path involving motion oblique to the maximum dip direction, and parallel to the constraining transverse fault zones.

The constraint of decompacting in fixed vertical columns does not take into account bedding plane rotation. Given that translation of any decompacted point on a bedding surface is assumed to be parallel to the slip vector on the CSF, decompaction of vertical columns results in the removal of thinner overburden columns for any particular sequence than would in reality have have been acting on the reference point prior to the later rotation (figure 3.16). The error in bed thickness resulting from this effect is proportional to the cosine of the rotation angle. The maximum tilt at the base of the NTEG is 18 degrees, resulting in errors of the order of 5 percent.

The decompaction and reconstruction of motion on the CSF (figure 3.15) raised a number of important points, of relevance either to the decompaction procedure itself and the errors introduced therein, or to the kinematic evolution of the CSF. These are summarised as follows:-

(1) Subsidence in the Triassic was far greater than is suggested by the uncorrected thickness on the depth section. If a substantial thickness of Upper Palaeozoic sediments underlies the Base Zechstein in the NTEG, then part of the Triassic subsidence may be explained by compaction of this sequence.

(2) In the claystone sequences, the rate of compaction over the first 2000 metres of burial far exceeds that at greater depths. Since three of the intervals have decompacted thicknesses in excess of 2000 metres, their progressive re-compaction appears less significant than might be expected from the porosity-depth curves. The Volgian, for example, had an initial thickness of 2000 metres, and subsequent burial under the Lower and Upper Cretaceous, and the Lower and Upper Tertiary reduced this to 1700, 1400, 1300, and 1200 metres respectively. This gives a reduction in thickness of 40 percent. The final burial depth of the Top Volgian is over 4000 metres, where from the curve of Sclater and Christie (1980) the porosity should be 8 percent, assuming a normal compaction gradient. Subtraction from the surface porosity of 65 percent then gives a reduction of 57 percent, and assuming an equivalence of loss of porosity and bed thickness reduction, the calculated change in thickness of the Volgian is some 30 percent less than predicted. The percentage reductions in thickness of the Triassic, Middle Jurassic and early Upper Jurassic sequences are 31,30, and 18 percent respectively. This discrepancy between expected and calculated thickness changes on compaction points either to a significant error in the decompaction procedure or to an invalid initial assumption. The compaction exercise is constrained to return the section to its input configuration, so one possible explanation of the thickness reductions is that having decompacted the deeper sequences by a certain amount, the decompaction

of the shallower sequences was forced to under-decompact in order to obtain the final depth values. Another possible source of error is the large interval thicknesses used in single iterations, but these should be systematic and proportional to the final thickness of a given sequence. Perhaps the simplest explanation of the discrepancy is that parts of the pre-Upper Cretaceous section are under-compacted i.e overpressured, a supposition which is entirely reasonable considering the high rates of sedimentation during the Volgian and the absence of any basin-wide aquifers within the predominantly shaly sequence.

(3)The Upper Cretaceous sequences form a monocline above the buried fault scarp (figure 3.17). The structural relief across this fold decreases progressively from 440 metres at the Base Upper Cretaceous to zero at the Base Upper Oligocene. Apart from some limited onlap of the early Chalk, the sequences are observed to drape the fold, suggesting a persistent rejuvenation of the structural relief during the Late Cretaceous and Early Tertiary. Sea floor relief across the fault scarp was a minimum of 500 metres at the beginning of the Cretaceous, but this was filled by onlap by the Santonian (figure 3.17). This suggests that the monocline is a growth feature formed by the progressive differential compaction of the hanging wall during Early Tertiary burial. The observation that loading of the hanging wall by nearly 3,500 metres of sediment produced only c.500 metres of differential compaction relative to the rigid footwall, favours the notion that a considerable part of the Upper Jurassic sequence is overpressured.

3.3.3 Displacement History of the CSF.

The displacement of the CSF was measured in the line of section parallel to the fault on each of the reconstructed sections. These

values are plotted against time in figure 3.18. This plot shows that there were two main phases of displacement, separated by an Early Jurassic hiatus. The displacement rates differ considerably in these two phases. Allowing for the uncertainties in the absolute value of Late Jurassic subsidence owing to the possibility of overpressuring, the graph nevertheless shows a pronounced acceleration in displacement in the Volgian, at a time when the relief on the fault scarp is thought to have increased, and when fans distributed the products of erosion of the footwall on the basin floor (Chapter 2.6). The acceleration in displacement is thus connected to a re-ordering of the rift depositional systems. As has been suggested in Chapter 2.6, it is probable that the increase in the rate of slip induced an accentuation of the footwall uplift, and the increase in tectonically controlled relief outpaced the ability of sedimentation to maintain the earlier equilibrium. This imbalance then led to steep gradients on the depositional surface and the triggering of gravity flow depositional processes. The dynamic significance of the contrasting displacement rates of the two phases of slip, and the implications of the magnitude of the displacement rate for studies of continental deformation are considered in Chapter 5.

3.4 THE FEDA GRABEN.

The Feda Graben is one of a series of rhombohedral fault bounded basins that collectively form the NW-SE trending Central Graben. Gowers and Saeboe(1985) regarded the Gert Ridge as the north-eastern boundary structure and the Lindesnaes Ridge as the south-western boundary (figure 1.3). In the description presented here, the much larger Mandal Fault is taken as the north-eastern boundary, and the Gert Ridge is viewed as a subordinate axial fault zone separating two distinct graben blocks. In

the Danish Sector, the Feda Graben is symmetric, and comparable Late Jurassic and Early Cretaceous depocentres are clustered against the two margins. In the Norwegian Sector however, the graben is markedly asymmetric, and the Late Jurassic and Early Cretaceous sequences thicken towards the Lindesnaes Ridge (Gowers and Saeboe, 1985).

The two margins of the Feda Graben have contrasting structural geometries. On the north-eastern margin, the structure is dominated by the Mandal Fault. This fault is planar at depth, dipping approximately 30 degrees, steepening at shallow structural levels to give a superficially listric appearance (Enclosure 22). A planar splay fault cuts at a tangent to the shallow listric fault surface, and continues into the Mandal Fault (Enclosure 12). This geometry suggests that the listric form of the upper part of the fault plane developed by collapse in the hanging wall of the original planar basement fault (Gibbs, 1984). A major basement fault branches off the WNW trending Mandal Fault near the intersection with the Lulu Transverse Zone, and assumes a NNW trend along the 'root' fault of the Jens-Otto Fault Zone (section 3.2.5, Enclosures 2 and 3).

Seismic-stratigraphic analysis of the fill of the north-eastern block of the Feda Graben indicates that the Mandal Fault first began to influence deposition in the Oxfordian (Chapter 2.6). This is evidenced by the onlap of a divergent Upper Jurassic sequence on an eroded Middle Jurassic and Triassic substrate (figure 3.20, Enclosure 12). Active displacement on the Mandal Fault ceased at the end of the Jurassic, and Lower Cretaceous sediments thin towards the upper tip of the fault from a small hanging wall depocentre (figure 2.47b, Chapter 2.7). Minor

offsets of the Base Cretaceous across the inactive tip of the Mandal Fault are attributed to differential compaction or isostatic adjustments to sediment loading.

The south-western margin of the Feda Graben is also bounded by a large basement fault. Near the Norwegian border it is sub-vertical, with shallowing upward strands passing up section into a Late Jurassic monoclinal fold (Enclosure 12). Along strike to the south-east, the fault is a simple planar surface dipping approximately 40 degrees (figure 2.31). The maximum throw is approximately 3000 metres, and this decreases rapidly along strike in both directions (Enclosure 9). The fault dies out immediately east of P-1, and the rapid decrease in displacement is accompanied by a general shallowing of the graben floor towards the Dogger Platform. The boundary between the Feda Graben and the Dogger Platform is marked by rapid lateral thickness and facies changes in the Upper Jurassic sequence (Enclosure 9), and by a pinch-out of the Lower Cretaceous sequence (Enclosure 10). This boundary between a relatively stable block (the Dogger Platform) and a rapidly subsiding block has a much more diffuse structural expression than in the case of similar block to basin boundaries along the margins of the Tail End Graben. The boundary in this case was not an abrupt hinge zone or fulcrum, but more a gentle monocline, and the north-westward plunge of the Feda Graben occurs over a broad transitional area (Enclosure 3).

Differences in the stratigraphy of the south-western and north-eastern blocks of the Feda Graben have been described in detail in the previous chapter. A fairly complete Mesozoic sequence is preserved south-west of the Gert Ridge, whereas to the north-east, early Mesozoic sequences are severely truncated at the basal Upper Jurassic

unconformity (Chapter 2.6). The reflection configurations of the Upper Jurassic are also markedly different on either side of the Gert Ridge, changing from parallel in the south-western block to divergent in the north-eastern block, which is suggestive of a system of differential subsidence of the two blocks hinged at the axial fault zone along the Gert Ridge (figure 3.20). It is considered that the differential motion of the two hanging wall blocks was taken up along the Gert Ridge in much the same way as the transverse fault zones in the Tail End Graben took up the torsional strain between the differentially rotating graben segments.

The structure of the Gert Ridge is complex. It is composed of 'root' faults with west and east-dipping polarities, combining to give a conjugate cross-sectional appearance. The sense of the dominant polarity changes along strike (figure 3.19). In the Norwegian sector, the downthrown side is to the north-east, but just inside the Danish border, this switches to the south-west (Enclosures 3 and 4). From the evidence of Upper Jurassic growth indices on the component faults, it is clear that the faults were active in the Late Jurassic, during the phase of differential subsidence on the two hanging wall blocks (Enclosures 9 and 12). Earlier activity can not, however be excluded, although the resolution of the pre-Upper Jurassic sequences is too poor to positively identify any deeper growth components. The fact that the Gert Ridge shares the same WNW-ESE trend as the graben bounding structures, again raises the question of basement inheritance, and increases the likelihood of there having been some earlier activity along this structure.

A reconstruction of the structural evolution of the Feda Graben is summarised in figure 3.20.

3.5 THE DOGGER PLATFORM.

The Dogger Platform can be regarded as typical in many respects of an intra-rift platform or high (Rosendahl et al.,1986), in that it was never a fully subsiding element in the manner of the bordering Feda and Tail End Grabens, but neither was it a fully emergent, positively uplifted block, in the manner of the rift shoulders. The relative stability of the platform ensured that the depositional surface was at or near sea level for much of the Triassic and Jurassic, which amplified the effects of any variation in absolute sea level. Small scale faulting during deposition, fault block rotation and erosion were additional factors influencing the complex stratigraphic evolution of the Dogger Platform (Chapter 2.6).

The Dogger Platform is intensely faulted. The faults are normal, and have small to intermediate throws (100 to 1000 metres). Growth indices on these faults are known only from the Upper Jurassic sequence. In many examples, the early part of the Upper Jurassic is marked by divergence towards the faults, and the later part is characterised by onlap and thinning, possibly onto abandoned fan systems (figure 2.27). The stratigraphic and structural relationships depicted on figure 2.27 are typical of the many rotated fault blocks on the platform. The ages of the various unconformities observed in the small hanging wall depocentres are not known. Direct correlation of the unconformities with the thick Jurassic succession of the neighbouring grabens is rendered impossible by the intense fracturing and lateral changes in seismic facies across the hinged margins bordering the platform (Chapter 2.6, figure 2.30). The fragmentation of the platform into the host of

rotational fault blocks was coeval with the acceleration in rotational subsidence in the Tail End Graben in the Oxfordian.

The intra-platform normal faults strike predominantly NW-SE (Enclosures 2 and 3). In cross-section the rotational fault blocks resemble the domino fault systems described in recent reviews of extensional tectonics (Morton and Black,1975; Wernicke and Burchfiel,1982). On any particular seismic line across the Dogger Platform, the normal faults dip either to the north-east or the south-west, but conjugate forms are only rarely seen in a single section. The sense of the domino tilt changes at intervals in a transect along the Dogger Platform (figure 3.21). The positions where the polarity of the fault block rotation changes coincide exactly with the projections of the segment boundaries in the Tail End Graben. If the Dogger Platform was partially coupled to the Tail End Graben, such that motion of the graben was somehow translated via the adjacent crustal block (the Dogger Platform), then it is reasonable to expect the internal fragmentation of the Dogger Platform to have been ordered in a segmented form comparable to that of the Tail End Graben. The differential rotation of the segments of the Tail End Graben would then be expressed in longitudinal variation in structural style of the Dogger Platform, which is exactly the pattern that is observed. It is considered that whilst most of the rotation of the NTEG and CTEG was hinged at the fulcrum along the Jens-Otto Fault Zone, part of the torsion between the graben segments was transmitted into the Dogger Platform. This stimulated the fragmentation of the Dogger Platform into the families of rotated fault blocks, which tilted without themselves undergoing significant vertical motion to give simultaneous erosion of the apices and deposition in the hanging walls.

3.6 THE OLAF FAULT ZONE, AND THE OUTER ROUGH BASIN.

The Olaf Fault Zone (OFZ) is a NW-SE trending corridor of deformation, expressed at a variety of structural levels, consisting of major and minor normal faults, reverse faults, folds, and horst blocks. The OFZ links to the north-west with the Lindesnaes Ridge, and is mapped as far south-east as the Jens-Otto Fault Zone (figure 3.21). The structural complexity of the OFZ stems from the intimate juxtaposition of two oppositely verging fault suites, which were subject to polyphase reactivations in a variety of senses. The structural evolution of the OFZ is extremely important in the wider context of the evolution of the rift since the earliest deformation identifiable from the seismic and well data along the structure is far older than on any of the other major structural elements of the Central North Sea.

3.6.1 Extensional Structures.

The Olaf Fault is a crudely en echelon series of WNW-ESE striking fault plane segments, that collectively define the north-eastern margin of the Outer Rough Basin (figure 3.21). The cross-sectional geometry of the fault plane varies along strike, particularly at shallow structural levels, but is consistently planar at depth, dipping between 25 and 40 degrees to the south-west (Enclosures 22 and 24). The geometry is constrained by sharply resolved, high amplitude fault plane reflections, which are accurately migrated with respect to bedding plane reflections from the highly reflective U.Palaeozoic sequence in the hanging wall (figure 3.22).

The hanging wall of the Olaf Fault is termed the Outer Rough Basin, specifically with reference to the half-graben fill of the Upper Jurassic and Lower Cretaceous (Enclosure 13, figure 2.4). The thick

U.Palaeozoic sequence preserved in the hanging wall is part of a platform succession that can be correlated over large parts of the Mid North Sea High, and ranges in age from Devonian to Middle Carboniferous. Immediately adjacent to the Olaf Fault, this parallel bedded sequence is broken up by a rhombohedral pattern of minor faults, oriented WNW-ESE, and NNW-SSE (figure 3.23). Some of these minor faults have throws which increase downward through the U.Palaeozoic sequence, and which are therefore regarded as having been active during deposition (figures 3.24, 2.4). In one or two instances, there are abrupt changes of seismic facies across the faults, which is further confirmation of the structural activity during deposition (figure 3.24). This syn-depositional activity on the hanging wall minor faults raises the possibility that the Olaf Fault was also active during the Late Palaeozoic. Subsidiary fracturing of the hanging walls of large normal faults is very common, and may result from irregularities in the geometry of the fault plane (e.g. Gibbs,1984; Harding 1984; McClay and Ellis,1987), as is very probably the case with the Olaf Fault, or from near field deformation associated with displacement gradients on the fault plane (Barnett et al.,1987). It is probable, therefore, that the development of the hanging wall fracture pattern was contemporaneous with a phase of displacement of the Olaf Fault in the Late Palaeozoic. As discussed in Chapter 2.2, from a comparison of the pre-Permian stratigraphy of the Dogger Platform/Dogger High and the Outer Rough Basin (figure 2.8), it is considered that the Olaf Fault was initiated in the Devonian or Early Carboniferous as an intra-basinal fault. This

recognition of activity as far back as the Early-Mid Carboniferous is extremely significant, since it shows that the WNW basement trend, which is so evident in the Jurassic structural fabric of the area, was active prior to the earliest recorded motion on structures with the rift-parallel NNW trend.

The Olaf Fault was dormant through much of the Mesozoic, but was reactivated firstly in a normal sense in the Late Jurassic/Early Cretaceous, to form the perched hanging wall basins, and then finally in a compressional sense during the Late Cretaceous basin inversion. The Upper Jurassic and Lower Cretaceous of the two hanging wall depocentres onlap the truncated Upper Palaeozoic sequence in the manner of parallel onlap fill (Chapter 2.7, figure 2.47c). The basal unconformity is only gently angular, and there is no indication of any major uplift and erosion on the immediately adjacent parts of the Mid North Sea High (Enclosure 17). If there had been any significant uplift of this western shoulder of the rift, there would undoubtedly have been a comparable tilting and bevelling of the U.Palaeozoic sequence to that observed from the shoulder of the Ringkobing-Fyn High (figure 2.42). The remarkable aspect of all the seismic lines in this promontory of the Mid North Sea High, is the near concordance of the U.Palaeozoic and Late Mesozoic sequences (Enclosures 12, 13 and 17).

The two Early Cretaceous basins in the hanging wall of the Olaf Fault (Enclosure 5, figure 3.21) are separated by a large anticlinal structure. Enclosure 17 is a strike line running parallel and adjacent to the Olaf Fault, and shows very clearly the anticline affecting the U.Palaeozoic sequence and the sharply angular, parallel onlap of the

Upper Jurassic and Lower Cretaceous. The mapped position of the anticlinal axis can be seen in relation to the Dogger High and the Olaf Fault on Enclosures 4 and 10. Remarkably, the dip line intercepts of the reflection emanating from the Olaf Fault also define an antiformal trace on the strike line, and this strike projection of the fault plane is concordant with the deformed hanging wall strata (Enclosure 17, figure 3.25). This configuration implies that the fault plane has a convex upward bulge which is mirrored in the shape of the Top Palaeozoic unconformity surface. The fault plane was reactivated in two separate portions, and the up-bulged central portion of the fault surface was completely unaffected by the later phase of extension. It is concluded, therefore, that the unusual shape of the fault plane was an important factor in the reactivation process.

A further point of interest with regard to the possible origins of the unusually shaped fault plane is that the NE trending anticlinal axis is co-linear with several 'anomalous' structural features further to the north-east, namely, the crest of the Dogger High, the pronounced sub-basinal axis in the south-western margin of the Feda Graben, the point of polarity change along the Gert Ridge, and the splay point of the Mandal Fault (figure 3.21). This overall NE trending alignment of anomalous features is evocative of a deep seated basement dislocation, that is perhaps too deeply seated to give rise itself to discrete fractures in the near-surface, but is nevertheless fundamental enough to exert a primary influence on the arrangement of shallower basement structures. In the absence of published structure maps from the U.K sector of the adjoining region of the Mid North Sea High, it is not possible to comment on the regional significance of such a basement dislocation, but a NE-SW trending lineament was interpreted from

magnetic anomaly patterns and bathymetric features along the inferred trace of this basement dislocation by Dikkers(1977).

The Dogger High is a diamond shaped basement horst, bound by the controlling faults of the Outer Rough Basin and the Feda Graben (figure 3.26). The horst plunges to the south-east, and the oppositely verging fault suites that flank the Dogger High coalesce to form the crossing conjugate fault structure termed here the OFZ (Enclosure 24, figure 3.26). Further again to the south-east, the two fault suites diverge once more, the north-east dipping Mesozoic faults assuming an E-W trend, whilst the south-west dipping U.Palaeozoic faults continue on a WNW trend as far as the Jens-Otto Fault Zone (Enclosure 2, figure 3.21).

The structure at the intersection of the OFZ and the Jens-Otto Fault Zone is extremely complex. Late Jurassic reverse components of displacement are observed on faults bounding small folds (figure 3.27), and the structural geometries are suggestive of local compressional features rather than more widespread regional convergence. It is difficult to establish the offset relations of the two sets of intersecting structures because of the wide grid spacing and the obfuscating effects of Late Cretaceous and Early Tertiary salt diapirism. A direct connection between the OFZ and the Dan Fault Zone seems at first sight from the structural mapping (Enclosures 2, 3 and 5) to be out of the question. However, when the possibility of minor lateral offsets of the WNW trending basement structure along the later, rift-parallel structures of the Jens-Otto and Gorm Fault Zones is taken into account, a remarkable alignment of the OFZ and Dan Fault Zone becomes apparent. The two fault zones together constitute a WNW-ESE

trending lineament over 100 kilometres long, which may continue further to the north-west along the Lindesnaes Ridge, and further to the south-east as a series of major basement faults in the Ringkobing-Fyn High (see Chapter 4). The reversal in polarities of individual faults along this 'basement corridor' precludes any significant horizontal translation during the Mesozoic. The length and continuity of this narrow 'corridor' of basement structures, and the repeated reactivation of the component structures, do, however, suggest that the lineament is a major, and possibly deep seated zone of basement dislocation.

The nature of the basement structure of the 'corridor' is suggested by the internal structure of the Dogger High. The Dogger High has a relatively thin cover of Mesozoic sediments (Enclosure 24), and consequently the basement structure in the core of the horst is clearly resolved on the seismic data. Far from being an integral structural unit in the manner typically associated with 'basement highs' such as this, the Dogger High is permeated by a network of criss-crossing faults that appear on the seismic data as a series of fault plane reflections emanating from within the crystalline basement (figure 3.28). The offset relationships of this conjugate system of intra-basement faults are complex, and because of the preferential imaging of one fault suite relative to the other, are sometimes difficult to interpret. The relationships change abruptly from one section to the next, over distances of only 2-3 kilometres. On figure 3.22, for example, a west dipping suite of faults forms the dominant reflection set, but these are clearly seen to be offset at fairly regular intervals by a conjugate east-dipping suite. This offset relationship persists for several kilometres along strike in both directions (SP 10 and SP12 on Enclosure 24), but then switches to the opposite sense (SP8 and SP14). On some of

the cross sections, the two suites mutually offset one another in a seemingly random way, as seen for example on figure 3.28. The interpreted conjugate configuration of this seismic line is illustrated in figure 3.29. On the western margin of the horst, fault 2 (east-dipping) offsets fault 1(the Olaf Fault) in a thrust sense, but at a slightly shallower level, fault 1 is itself reactivated in a thrust sense and offsets fault 4(east-dipping). In the core of the horst, fault 4 is then offset by fault 3(west-dipping). On the eastern margin, fault 5 (east-dipping offsets three west-dipping faults (6-8). Thus it can be seen that neither suite consistently offsets the other, from which it is inferred that the fabric is a crossing conjugate system (Horsfield, 1980).

Structural maps of U.Palaeozoic and Mesozoic levels (Enclosures 3 and 4, figure 3.23) show that normal faults in the vicinity of the Dogger High and along its margins are oriented WNW and NNW. Limited fault correlations made between conjugate faults in the core of the Dogger High indicate that the two fault suites are also oriented in these two directions, the suite dipping to the south-west striking WNW, and the suite dipping to the north-east striking NNW (figure 3.26). This similarity between the dips and orientations of the conjugate basement faults and the later basin bounding faults on the margins of the Dogger High suggests that the Late Palaeaozoic and Mesozoic extensional faults formed by the reactivation of an existing basement fabric (figure 3.30). The structural relations depicted on Enclosure 24 are strongly suggestive of several distinct phases of reactivation of the basement fault fabric, and the variation of the final structural geometry along the long axis of the horst apparent on this enclosure can be explained by the selective reactivation of favourably oriented elements of the

basement fabric. Late Palaeozoic extension primarily exploited the WNW trending, south-west dipping basement fault suite, and the Olaf Fault probably developed through the individual propogation and subsequent linkage of numerous sub-parallel basement fault segments. The complex geometry and en echelon trajectory of the Olaf Fault may thus stem from irregularities in the linkage of the inherited early structure (figure 3.31). Mesozoic extension on the other hand exploited both suites, with the principal bounding faults developing from the north-east dipping basement segments, and antithetics to these developing from the south-west dipping segments (figure 3.31). This process of reactivation of pre-existing basement faults explains why the large normal faults bounding the Dogger High have such low-angle geometries.

The nature of the basement fabric is a matter of speculation. The high amplitudes of the fault plane reflections indicate that the 'faults' producing the reflections must mark major lithological boundaries. High amplitude linear dipping reflections comparable to these have been described from the Outer Isles Thrust Zone in the Hebrides, and have been shown to emanate from mylonitic lithologies in basement shear zones (Peddy, 1984). It is suggested, therefore, that the faults cutting the basement core of the Dogger High are more likely to be shear zones than brittle faults.

P-1 was drilled on the crest of the Dogger High, and reached T.D in medium-high grade amphibolitic gneiss, which yielded an Ar-Ar date of 436ma (Ziegler, 1982). The basement of the Dogger High was evidently metamorphosed during the Caledonian Orogeny, and it is possible, therefore, that the pervasive conjugate shear zones formed during this tectonic phase. It is also possible that this fabric is extensional, and post-dates the Caledonian phase, but pre-dates the Late Palaeozoic basin

formation event. Similar mid-crustal basement fabrics have been described from the Basin and Range Extensional Province of the U.S.A (Hamilton,1987), and it is theoretically possible to form this kind of fabric under extension or compression (Ramsey and Huber,1987). It is not possible to decide between a possible extensional or compressional origin with the present data, but it is interesting to note that similar conjugate fabrics are also observed from the basement of the Ringkobing-Fyn High (Chapter 4), and from mid- and lower crustal portions of deep reflection seismic lines acquired over rift basins on the continental shelf of the U.K (personal observation). The importance of pre-existing basement anisotropy is considered further in Chapter 5, together with a review of the crustal structure of the U.K rift basins as it appears on deep seismic data.

3.6.2 Compressional Reactivation.

The OFZ was a major locus for compressional reactivation in the Late Cretaceous (Vejbaek and Andersen,1987; Cartwright,1988a). Structural and isochore maps of Upper Cretaceous levels show the structural relations of the numerous reverse faults and folds along the trend to be fairly complex, and the cross-sectional structural geometry changes considerably from line to line (Enclosure 24). The braided fault patterns, and crudely en echelon arrangement of folds have been cited as evidence of strike-slip deformation in the Late Cretaceous (Michelsen and Andersen,1983), but inspection of Enclosure 24 shows that the variation in structural style can be explained equally by the dip-slip reactivation of the conjugate basement fabric described previously from the Dogger High/OFZ. The close association between the polarity of fold vergence and the geometry of the basement fabric can be seen from the parallelism of inversion fold axes with the earlier extensional structure (c.f Enclosures 4 and 11).

A similar relationship between extensional and contractional structures was described from the JOFZ (see section 3.2.5), where it was also argued that this is compatible with dip-slip reversal of motion. If the kinematics of the reverse reactivation were oblique or strike-slip, it would be expected that the orientation of fold axes would be oblique to the strike of the extensional faults.

An important control on the Late Cretaceous structural geometries is the degree of overlap or separation of the major extensional faults. In the north-west (e.g SP 10 on Enclosure 24), the two oppositely dipping basement faults are widely separated by the intervening Dogger High, and the thrust/fold vergence is inwards towards the crest of the high. In the south-east, however, where the basement faults merge towards one another as the horst plunges towards the south-east, the upward propagation of the compressional reactivants produced a coalescing double pop-up fold (SP 20 and SP 22).

The vergence of thrust/fold pairs on most of the inverted margins of the Danish Central Graben is from the basinal areas towards the adjoining highs. However, along the OFZ, the network of intermeshing shear zones represented a host of potential reactivation surfaces, and thrust faults propagated outwards from the core of the horst as well as inwards over the margins of the horst. The most spectacular example of oscillatory 'forethrusting' and 'backthrusting' can be seen in the crestal region of the Dogger High (Enclosure 24, figures 2.4 and 3.28). The initial reactivation of the Olaf Fault was in a forethrust sense giving rise to a north-east verging asymmetric fold in the hanging wall. This was followed by the 'backthrust' reactivation of two of the north-east dipping shear zones in the core of the horst, which offset the Olaf Fault and formed two minor thrust-tip folds in the hanging

wall with the opposite vergence to the earlier fold. Alternating or even simultaneous reactivations of the two conjugate basement shear zones suites can thus explain the curious and unusual compressional geometries, without recourse to the universal panacaea of strike-slip tectonics.

CHAPTER FOUR: A RECONNAISSANCE STRUCTURAL INTERPRETATION OF THE RINGKOBING-FYN HIGH.

4.1 INTRODUCTION.

The Ringkobing-Fyn High (RFH) is a WNW-ESE trending series of shallow basement horsts transected by a succession of NNE trending rifts, which together with the Mid North Sea High forms one of the major structural elements of the North Sea (figures 1.1 and 4.1). The two major highs link to form a barrier between the Northern and Southern Permian Basins. It is generally accepted that the highs were formed during a Late Carboniferous-Early Permian tectonic event (Ziegler, 1982), but there have been relatively few attempts at explaining the dynamics of the structural uplift. Existing hypotheses for the cause of the uplift range from the resurgence of buoyant granitic masses at the core of the highs under a regionally tensile stress field (Donato et al.,1983), to flexural rebound related to thrust loading of the Variscan Foredeep (Ziegler,1982; Dewey,1982; Pegrum,1984a). These hypotheses have been based largely on regional geological considerations rather than on the specific geology of the highs themselves. The highs have generally been considered to be unprospective for hydrocarbons, and this has meant that until very recently there has been only limited acquisition of well and seismic data. The advent of large regional speculative seismic surveys has vastly improved the data coverage to the extent that it is now possible to map the major structures using sub-surface data, and hence test the various tectonic reconstructions of the area.

One of the key problems addressed in this thesis is the origin of the kinked rift fracture pattern of the Central North Sea. In the preceding chapters, it was established that the Danish Central Graben is

transected by several WNW-ESE trending basement fault zones. These served to segment the rift at the transitional zone of re-orientation from one rift axis to the next. It was also demonstrated that these transverse fault zones were inherited from pre-existing basement structures, and were active prior to the initial rupturing along the rift-bounding faults. The implication of these relationships is that the adoption of the the kinked trajectory by the rift is related in some way to the presence of the transverse fault zones. The main objective of this chapter, therefore, is to establish a structural framework for the RFH, and so explore the nature of the connection between the structural evolution of the Central North Sea Highs and that of the associated transecting rifts. The wide spacing of the available seismic grid precludes the same level of detailed structural mapping described in the previous chapters, and consequently this chapter is based largely on the reconnaissance mapping and description of the major structures.

4.2 MAJOR BASEMENT STRUCTURES.

The reconnaissance seismic interpretation shows that far from being a large coherent basement horst, as commonly portrayed on maps of the pre-Permian geology of the North Sea (e.g Ziegler,1982), the RFH has a complex basement fracture pattern, composed primarily of large WNW and NNE trending normal faults (figure 4.1). The northern and southern margins have been defined by this mapping as being composed of linear zones of faults with an overall WNW trend, confirming the early megatectonic interpretation made by Dikkers(1977) from lineament analysis of gravity and aeromagnetic anomalies.

The northern and southern margins of the RFH as defined in Jutland are referred to as the Vinding and Romo Fracture Zones, respectively. At intervals of between 80 and 100 kilometres along the axis of the RFH,

the marginal fracture zones are intersected, and in some cases offset by NNE-SSW trending basement faults forming the controlling structures for the Late Palaeozoic and Early Mesozoic grabens. Considerable thicknesses of pre-rift sediments are preserved in these grabens, whereas on the neighbouring horsts, the pre-rift sequence was subject to intense erosion primarily during a phase of uplift and tilting accompanying the formation of the rifts. The excellent definition of the reflective pre-rift sequence not only facilitates the long-range fault correlations required by the spacing of the seismic grid, but also gives a clear indication of the level of intensity and mode of deformation of the basement.

4.2.1 The Fracture Zones.

The Vinding Fracture Zone (VFZ).

The VFZ was first described by Dikkers (1977) as a prominent aeromagnetic lineament extending from eastern Jutland along a WNW trend to the Norwegian border, which he termed the Vinding Line. The new term is introduced here partly for added descriptive value, but also partly to distinguish a recognised structural entity, the northern boundary structure of the RFH, from an aeromagneic anomaly that coincides with the structure along most, but not all of its length (figure 4.1).

In Central Jutland, the basement feature expressed in the magnetic and gravity anomalies appears at shallow crustal levels as a 10-15 kilometre wide zone of intense basement and cover faulting (Enclosure 20d). This zone of faulting delimits the southern edge of the Northern Permian Basin (Berthelsen,1980). The VFZ is mapped offshore to the west as a zone of intense faulting, tilting, uplift and truncation of a platform sequence of parallel-bedded Upper Palaeozoic sediments (Enclosure 20(a,b), figure 4.2). The VFZ intersects and offsets the

boundary fault of the Northern Horn Graben, and continues along the WNW trend as far as the boundary fault of the Northern Else Graben (figure 4.1). At this point, the VFZ swings abruptly round to a WSW trend, and in addition, the polarity of the major basement normal faults within the VFZ changes from north-dipping to south-dipping (figure 4.1). The VFZ continues along this new trend towards the uplifted shoulder of the Danish Central Graben, but the severe attenuation of the Upper Palaeozoic strata on the shoulder prevents the straightforward identification of basement faulting. There are indications of disruption within the crystalline basement immediately adjacent to the Coffee Soil Fault, however, and it is considered probable that the VFZ continues as far west as the Coffee Soil Fault.

It is interesting to note that the projected continuation of the VFZ along the zone of basement disruption gives an intersection precisely at the point of strike re-orientation of the Coffee Soil Fault at the Lulu Transverse Zone (figure 4.1). If this projected continuation is valid, it suggests that the VFZ has the same intersecting relationship with the Tail End Graben that it has with the Northern Horn Graben. It should also be recalled that a deep basement lineament was postulated to run along a NE to ENE trend beneath the Outer Rough Basin, the Dogger High and the Mandal High, along the path of a major bathymetric lineament termed by Dikkers(1977) the Dogger Line (figure 4.1). Is this convincing alignment of intra-graben basement horsts, transverse fault zones and the VFZ purely coincidental, or does it hint at a more fundamental aspect of the major basement lineament with regard to the fracture development in the rift?

A representative section across the VFZ showing the main features of the structure and stratigraphy is illustrated in figure 4.2. The VFZ is recognisable as a fairly broad zone of faulting affecting the platform Upper Palaeozoic sequence. The offsets across the constituent faults of the zone are large and almost exclusively normal, as can be seen, for example, on figure 4.2, and the basement structure is readily identifiable by correlating the high amplitude event marking the acoustic basement. This high amplitude basal sequence boundary and the parallel-bedded sequence above are remarkably similar to the parallel-bedded Devono-Carboniferous sequence described from the Mid North Sea High (Chapter 2.2), and it is postulated, therefore, that the sequence observed on the RFH originally formed part of a single large depositional province that may have extended over the entire southern and central North Sea (figure 2.3).

Many of the component faults of the VFZ are truncated at a major angular unconformity forming the base of the fill of the Northern Permian Basin (figure 4.3). This basal unconformity is commonly termed the Saalian Unconformity (Ziegler,1982), is a prominent truncation surface throughout the RFH (Enclosure 20), and was formed during the major phase of uplift and denudation during the Late Carboniferous-Early Permian tectonic phase (Ziegler,1982). The angularity and degree of truncation of the underlying Upper Palaeozoic sequence is far more severe across the VFZ, however, than over the adjoining basement horsts. The geometry at the unconformity along the VFZ (figure 4.3, Enclosure 20), suggests that large scale uplift and denudation took place immediately prior to the onset of subsidence and deposition in the Northern Permian Basin. The truncation geometries are compatible with total net uplift of the axial part of the VFZ of between one and three

kilometres (figure 4.4). Whilst the cross-sectional structure at pre-Saalian levels is almost exclusively extensional, it is difficult to reconcile such extreme localised uplift as this with a purely tensile stress regime. Indeed, the combination of a wide, linear zone of basement faulting, rotation and uplift, with often downward converging external bounding fault strands (figure 4.2), and the often intense levels of internal detachment faulting exemplified on figure 4.3, is much more likely to have resulted from an obliquely divergent or even horizontal sense of relative motion of the crustal blocks juxtaposed along the VFZ.

Following the major regional phase of Late Carboniferous-Early Permian deformation, the function of the VFZ was kinematically simple: it functioned as a hinge zone separating the steadily and slowly subsiding Northern Permian Basin from the static RFH. The Zechstein marginal to basinal facies transition is located along one of the reactivated basement faults of the VFZ along much of the northern margin of the RFH (figures 4.1 and 2.26). The Triassic thins on to the RFH in a stepwise fashion across reactivated elements of the deeper part of the VFZ, without appreciable basal or internal onlap (Enclosure 20). The gross form of the pinch-out of the Triassic on to the RFH can best be described as a condensed drape: the implication being that the RFH was maintained at or very near sea level for much of the period, and was not the site of any significant absolute uplift. It is clear that the RFH was only a 'high' in the strictest sense of the term during the Late Carboniferous-Early Permian tectonic phase, at the time of the massive fracturing and truncation of the platform Upper Palaeozoic sequence. Thereafter, the RFH was simply a rigid massif flanked by two positively subsiding basins (figure 4.5).

The reactivation of elements of the VFZ continued well into the Tertiary. Large salt withdrawal structures formed during the Late Cretaceous and Tertiary along the VFZ (e.g figure 4.6). It is not certain what caused this late phase of halokinesis, but the localisation of salt withdrawal faulting to the deeper basement faults of the margin of the RFH is perhaps suggestive of some minor readjustment motion of the RFH 'massif' with respect to the weaker crustal blocks in the surrounding region. Minor dislocation and jostling of the large crustal blocks in the North Sea has been advocated as a possible mechanism for the Late Cretaceous and Early Tertiary Basin Inversions (Ziegler,1982), and it is conceivable, therefore, that the seemingly innocent halokinesis along the VFZ belies a more fundamental activity.

The Romo Fracture Zone (RFZ).

The RFZ is most clearly defined as a structural entity in South Jutland where it is found to be associated with a major, linear WNW trending magnetic anomaly and a steep gravity gradient (figure 4.7, Enclosure 20(d)). The structure is similar to that described from the VFZ, and the deeper basement faults show the same type of reactivation control on the depositional limits of the northern margin of the Southern Permian Basin as did the VFZ on the Northern Permian Basin. The potential field anomalies are attributed to the presence of a major crustal province boundary at depth, and recent refraction seismic data suggest that this boundary is a narrow, vertical fault zone at depth which offsets the base of the crust, and separates two markedly contrasting types of continental lithosphere (Clowes et al.,1987, and figure 4.8).

The westward continuation of the RFZ into the North Sea is suggested by alignments of major basement faults that follow a prominent WNW trend along almost the entire southern margin of the offshore part

of the RFH. A network of WNW trending basement faults which show evidence of strike-slip reactivation during the Mesozoic are mapped from the island of Romo to the hinged eastern margin of the Southern Horn Graben (figure 4.1). This alignment of basement faults appears to terminate in the axis of the graben along a boundary fault system separating the two southern segments of the Horn Graben (figure 4.9). Thereafter, the WNW trend is taken up by a major splaying basement fault which clearly offsets the large west-verging boundary faults of the two southern segments. Not only does this WNW trending fault offset the rift bounding faults, but across this intersection there is an abrupt change in orientation of the boundary faults from a NE-SW to a N-S trend (figure 4.9). The WNW trending fault continues for 60 kilometres along strike and has a large northward heave at basement levels, but further to the west, the fault terminates abruptly and a series of bifurcating basement faults throwing down to the south takes up the identical trend (figure 4.1, Enclosure 20(b)). These basement faults preserve considerable thicknesses of the platform Upper Palaeozoic sequence that were more completely eroded over the adjacent basement horsts. The truncation geometries of the Saalian Unconformity are comparable in magnitude and sense to those described from the VFZ, suggesting a harmony in the deformation styles of the two fracture zones. Given the striking WNW trending alignment of braided basement faults from Romo to the Else Graben, over a distance of some 250 kilometres, it is concluded that this alignment of faults constitutes the westward continuation of the RFZ into the North Sea.

Further to the west, the WNW trending fault zone appears to terminate at the margins of the Else Graben (figure 4.1). The projected point of intersection coincides directly with an intensely faulted zone

in the axis of the graben which is thought to mark the boundary between the two oppositely inclined segments of the Else Graben (figure 4.10). The seismic grid in this area between the Else and Tail End Grabens is too coarse to allow any definitive correlation of faults identified in the crystalline basement, but it is nevertheless considered that the similarity in the alignments of the RFZ and the Adda Fault Zone is too striking to be a coincidence. The intervening basement horst forming the peneplained eastern shoulder of the Tail End Graben is permeated by fault plane reflections, and whilst much of the basement deformation is expressed as low-angle thrusts or shear zones (see section 4.2.3), it is quite conceivable that an obliquely intersecting set of basement faults connects the RFZ and the Adda Fault Zone. The confirmation of this connection must await a tighter grid in this western sector of the RFH, but it is interesting to consider that both the VFZ and the RFZ are mapped with confidence virtually to the borders of the Central Graben, and their projected intersections with the Central Graben would in both cases be at points of transverse segmentation (figure 4.10). Furthermore, this postulated relationship between lineaments and segment boundaries is a consistent feature of the Horn, Else and Central Grabens.

4.2.2 The Horn Graben.

The Horn Graben is a NNE trending rift that opened during the Late Carboniferous to Early Permian tectonic phase, and continued to act as a major depocentre until the end of the Triassic (Ziegler,1982; Olsen,1983). The Horn Graben is segmented, and the major basement border faults display a range of orientations about the mean NNE-SSW trending rift axis (figure 4.9). The development of the segmented form is closely connected to the intersection of the RFZ and the VFZ. The segment boundaries are intensely faulted zones several kilometres wide, which have a WNW trend, although individual faults often more closely follow

the trends of the faults bounding the margins of the respective segments (figure 4.9). The outer segment boundaries appear to be almost direct continuations of the RFZ and the VFZ, although the precise offset relations between the transverse and the rift-parallel fault systems are not clear.

Each segment has a distinctive rift fill, and the differences in the fill characteristics are attributable to changes in the geometry and the displacement patterns of the major border structures. These differences are immediately apparent from a series of type cross sections across the four segments (figure 4.11). The southern segment is strongly asymmetric with divergent fill towards the west (figure 4.11(a)), but across the intersecting RFZ, the form becomes more symmetric, albeit with a fine scale asymmetry imposed by a series of closely spaced domino-style fault blocks (figure 4.11(b)). This highly faulted segment is bound by NNW trending basement faults, in contrast with the NE trending basement faults of the western margin further south. The syn-rift displacement on the NNW trending western border fault is a maximum at the intersection with the RFZ, but decreases rapidly northwards towards the zone of polarity reversal (figure 4.12). The maximum displacement on the western border fault of the southern segment is also observed adjacent to the intersection.

The distribution of net displacement along the two variably oriented fault plane segments differs considerably from the more usual centralised patterns of displacement observed on normal fault surfaces (Barnett et al.,1987). The form of the skewing of the displacement towards the intersection of the RFZ suggests that the mechanical perturbation represented by the fracture zone exercised a significant control on the means by which displacement proceeded on the two

simultaneously active bounding faults. Torsional strains within the adjacent graben segments and along the RFZ would have been required in order for the displacement on the border faults to have accrued to give the final configuration, and it is possible that the often intense faulting of the graben fill adjacent to the RFZ is the expression of that torsion (figure 4.13).

The boundary between the two central graben segments is particularly interesting in that it constitutes a zone of interchange of polarity in the inclination of the major rift border faults (figure 4.9). This type of polarity 'flip' is being increasingly recognised in continental rifts (Rosendahl,1986; Cartwright,1988b), but as yet there have been no detailed structural analyses of this phenomenon. In the central two segments of the Horn Graben, the displacement on the two oppositely verging border faults decreases towards the segment boundary. This loss of net displacement (and extension) is partly taken up by the development of splaying networks of minor faults branching of the major border faults in the immediate vicinity of the segment boundary.

Strike seismic lines running along the graben axis show that the structure of the segment boundary is an intensely faulted dome which was severely eroded at the pre-rift Saalian Unconformity (Enclosure 20(c)). The splay faults curve away from their primary rift-parallel orientation to form the crestal collapse faults of the domal structure. The geometry and truncation relationships of the dome are indicative of a net positive uplift of this axial part of the Horn Graben of 2-3 kilometres. In addition, the axial dome appears on aeromagnetic maps as an area of high magnetic intensity. Late Carboniferous-Early Permian volcanic rocks were encountered close to the Saalian Unconformity in the R-1 well, but it is not clear whether they were erupted prior, during, or immediately after the strong phase of uplift and erosion. Nevertheless, it is clear

that the intense magnetic signature is related to the presence of a considerable thickness of extrusive magmatic rocks whose eruptive locus was the axial dome of the central Horn Graben. The close spatial and temporal association of doming, magmatism, and nucleation of oppositely inclined rift fractures suggests that the development of the bi-polar graben form is causally linked to the formation of the domal structure. Furthermore, the location of the dome exactly mid-way between the bounding fracture zones of the RFH seems too symmetrical to be a coincidence, and suggests that the WNW trending fracture zones are also intimately connected with the doming and initial rift propagation. This notion gains further credence when it is recalled that the main fracturing and tilting within the two fracture zones also took place during the Late Carboniferous-Early Permian tectonic phase.

4.2.3 The Else Graben.

The Else Graben has a bi-polar form equivalent to that described for the two central segments of the Horn Graben (figure 4.1). The oppositely inclined basement faults controlling the half-graben geometries of the two segments also meet in an intensely faulted axial domal structure (Enclosure 20(a)). The southern segment is bound to the east by a basement fault that is steeply inclined in its upper part, but flattens at depth into a low amplitude fault plane reflection dipping 10 degrees to the west (figure 4.14). Beneath the floor of the graben and the adjacent footwall, the basement is permeated by similarly oriented, sub-parallel fault plane reflections, which occasionally anastomose to produce lensoid areas of zero reflectivity (figure 4.14). The reflection amplitude of this suite of dipping events is highly variable, and is suggestive, therefore of lateral heterogeneity in the lithological

contrasts from which the reflections emanate. The suite of fault plane reflections has an imbricated structural geometry, although in a strict sense there is no evidence of a basal sole plane to the fault suite. Nevertheless, in cross section (figure 4.14) the anastomosing and braided relationships exhibited by the closely spaced sub-parallel faults are strongly reminiscent of imbricate thrust systems as described from both crystalline and sedimentary lithologies (e.g Boyer and Elliott 1982), and it is suggested, therefore, that the basement underlying the Else Graben forms part of a large thrust complex. The deepest event can be traced to a depth of approximately 10 kilometres into the crystalline basement, but beyond this depth, the high noise/signal ratio on the record sections does not permit the discrimination between genuine reflections and migration artefacts (figure 4.14). It is conceivable, therefore, that the 'imbricate' zone continues at depth, beyond the limits of seismic resolution, and a basal sole plane to the imbricates observed in the shallow part of the crystalline crust lies at mid- or lower crustal levels. Alternatively, it is possible that the imbricates form part of a thick skinned contractional structure which, from the scale of the shallower resolved structures, may well extend throughout the entire crust. These two equally plausible interpretations of the fault plane reflection suites are illustrated in figure 4.15.

The seismic expression of the fault plane reflections is similar to that described in Chapter 3 for the conjugate set of dipping reflections in the core of the Dogger High. These were compared to the inclined sets of reflections observed on deep reflection profiles acquired by the BIRPS group, which are generally equated with ductile shear zones composed of mylonitic rocks. The fact that the 'fault planes' of the 'Else Imbricates' give rise to discrete reflections,

implies that the either the faults juxtapose basement lithologies of greatly contrasting density and velocity, or that the 'faults' themselves represent a lithological banding. The observed lateral variability in amplitude of the reflections could be accounted for in either of these two cases, but it is considered extremely improbable that the imbricate structure could have evolved in an entirely brittle deformation, and that the brittle juxtaposition of contrasting basement rock types could then have been so fortuitous as to yield as good a reflective representation of the imbricated structure as is finally observed. It is considered probable, therefore, that the imbricates are the product of ductile compressional deformation, and that the reflections emanate from mylonitic shear zones which formed under P/T conditions which were elevated sufficiently so as to favour the development of the distinctive shear zone lithologies (figure 4.16).

The west-dipping shear zones are observed on the seismic data throughout the basement massif bordering the Else Graben to the west, and also from beneath the graben itself, but beyond the bounding fault of the eastern margin of the graben, the basement is devoid of reflections. The relationship of the brittle faults forming the main graben structure to the underlying shear zones depicted on figure 4.14, implies that the graben developed through the selective reactivation of certain elements of the pre-existing shear zone imbricates (figure 4.17). The seismic data show that there are far more potential fracture surfaces in the form of the west-dipping shear zones than were actually required to form the foundations of the brittle extensional structure. This observation is further proof that the compressional basement structure pre-dated the opening of the graben, and that the imbricated 'faults' can not be the products of a brittle deformation. In

conclusion, the southern segment of the Else Graben is an excellent example of an extensional structure which formed by the reactivation of a pre-existing compressional basement fabric.

No such direct relationship can be established, however, for the northern segment of the Else Graben. The major bounding fault is on the western margin, and the thick Late Carboniferous-Early Permian rift fill sequence is strongly divergent towards this boundary fault (figure 4.18). The eastern margin is a structural and depositional hinge similar in many respects to the Jens-Otto Fault Zone (Chapter 3.2.5). The basement beneath the floor of the graben is buried beyond the limits of seismic resolution, and there is no clear indication in the shallower basement massif to the west of the graben of any comparable basement structure to that seen beneath the southern segment.

The seismic-stratigraphy of the two segments is summarised in figure 4.19. The northern segment of the Else Graben formed an embayment into the southern margin of the Northern Permian Basin, and the incursion of the basinal facies Zechstein deep into the interior of the RFH was evidently the result of active faulting on the Else Graben bounding fault (figures 4.1, 4.18, and 2.16). The activity on this fault ceased during the Early Triassic. In contrast, there is no evidence of Upper Permian or Triassic sediments in the southern segment, and it is therefore concluded that active fault controlled subsidence terminated much earlier in the south. However, the gross reflection characteristics of the pre-Upper Permian megasequence are comparable in both the segments, and whilst the total syn-rift thickness is far greater in the northern segment, the similarity in the form of the stratal geometries of the two segments indicates that the history of motion of the graben floor was similar in both cases. The rift-fill

megasequence is composed of two sequences, the lower of which is characterised in both areas by divergent reflection configurations with a generally low amplitude signature, whilst the upper sequence in both segments is characterised by parallel reflection configurations and high frequency/high amplitude and discontinuous reflection signature (figures 4.14, and 4.18). The boundary between these two sequences is a gently angular unconformity. In the absence of any well calibrations of this rift-fill megasequence, there is clearly an element of uncertainty in the interpretation of a Late Carboniferous-Early Permian age for the megasequence. The main lines of evidence for this interpretation (figure 4.19) are the concordant relationship of the upper part of the megasequence with the Upper Permian (see also Chapter 2.2), and the similarity of the seismic expression of the pre-Zechstein of the Else Graben to the pre-Zechstein of the Southern Tail End Graben (c.f figures 4.14 and 4.18, with figure 2.9). It is postulated, therefore that the Else Graben opened along the northern and southern segments during the Late Carboniferous-Early Permian concurrently with the initial phases of rifting in the Tail End Graben, the Horn Graben, and also the Oslo-Bamble Rift (Ramberg and Spjeldnaes,1978). The regional significance of this synchronous development of rifts transecting the RFH, anf the relationship to the uplift and fragmentation along the marginal fracture zones is discussed in Chapter 5.3.

4.3 THE EARLY ORIGINS OF THE BASEMENT STRUCTURE OF THE RFH.

The most important results of the reconnaissance mapping of the RFH are as follows:-

(1) The northern and southern margins of the RFH are defined by two major WNW-ESE trending fault lineaments, the RFZ and the VFZ.

(2) The earliest activity on these fracture zones recorded in the deformation of the sedimentary cover took place in the Late Carboniferous-Early Permian, and this resulted in the intense fracturing, tilting and erosional truncation of the platform Upper Palaeozoic sequence. It is not known whether there was any Devono-Carboniferous growth faulting along the marginal fracture zones, but the contrast in the gross reflection signature of the pre-Permian sequences across the VFZ in particular, may be an indication that the fracture zone was active in controlling the large scale basin morphology.

(3) The marginal fracture zones correspond to large gravity and magnetic anomalies, particularly in S.Jutland. The amplitude and wavelength of these linear anomalies is consistent with their interpretation as deep-seated vertical crustal province boundaries. In the case of the RFZ, the boundary is between the Mid-European Caledonides to the south, and Sveco-Fennides to the north. In the case of the VFZ, however, the shallow basement provinces are probably similar on either side of the boundary, but the cover sequences are markedly different: the northern block having a thick cover of Lower Palaeozoic sediments, whereas on the RFH, the Permian lies directly on the Precambrian crystalline basement.

(4) The linear trends of the two fracture zones are interrupted at intervals along their strike by their intersection with NNE-SSW trending bounding faults of the Horn and Else Grabens.

(5) These two grabens are segmented in a manner comparable to that described previously for the Tail End Graben. The positions at which the bounding faults change strike or sense are in almost all cases the points of intersection of the grabens and the fracture zones.

(6) The central two segments of the Horn Graben and the two segments comprising the Else Graben are arranged in a bi-polar form. In both grabens, the oppositely inclined basement faults interchange over areas of intense faulting of the basement and sedimentary cover. The gross structure of these areas is domal, and the pre-rift sequences are strongly truncated over the crest of the uplift at the Saalian Unconformity. Furthermore, there is evidence of considerable eruptive magmatic activity centred on the domal structures. The doming, erosion, fracturing, magmatism and initial opening of the grabens all occurred during the Late Carboniferous-Early Permian tectonic phase, but the precise temporal relationship between the magmatism and the fracture propagation is not known.

Several important questions arise from the observations summarised above. For example, does the continuity of shallow structural expression of the fracture zones from Jutland westwards into the North Sea necessarily imply that the crustal province boundaries interpreted from well and potential field data also continue as the deep crustal roots to the structural margins of the RFH in the offshore? How and when did these crustal boundaries originate, during the Silurian to Early Devonian, or even earlier? Why was Late Carboniferous-Early Permian wrench deformation taken up along these crustal boundaries? Is there a connection between the wrench deformation of the margins of the RFH, the uplift and erosion of the RFH, and the magmatism, segmentation and initial propagation of the transecting grabens?

The question of the early origins of the WNW-ESE trending fracture zones has been addressed recently by Pegrum(1984a), in connection with the structural evolution of the Tornquist Zone. Both Dikkers(1977) and Pegrum(1984a) have postulated that the margins of the RFH are fault

controlled, but whereas Dikkers(1977) considered that this tectonic lineation was subordinate to the main NE-SW Caledonide trend in the Central North Sea, Pegrum(1984a) has argued for a much greater influence of the Tornquistian structural elements in the tectonic evolution of the area than hitherto conceived.

The solution of many of the tectonic problems mentioned above lies in the question of the provinciality of the crystalline basement of the offshore part of the RFH. Existing recontructions of the early evolution of the Central North Sea can be classified into two main categories. The first group (figure 4.20) considers that the contact between the Mid-European Caledonides and the Precambrian basement of the Baltic Shield is a suture between the microcontinental fragments of Central Europe, which rifted away from a southerly Gondwana, and following the northerly subduction of the Rheic Ocean, collided with the cratonic shield of Baltica (Ziegler,1982; Cocks and Fortey,1982). The second group (figure 4.21) regards the contact between these two basement provinces as a transform plate boundary running along the line of the Tornquist Zone through Poland and mainland Denmark, and then either continuing on its north-westerly trajectory to the Orkney Islands (Pegrum,1984b; figure 4.21(A)), or curving on a WNW trending arc to link with the major Caledonian fault zones of Southern Scotland (Brochwicz-Lewinski et al.,1984; figure 4.21(B)). It is clear from the critical location of the Danish Sector as portrayed on the reconstructions illustrated in figures 4.20 and 4.21, that any possible means for discriminating between these contrasting reconstructions must lie in a clearer appreciation of the basement provinciality and structure of the RFH.

Direct evidence concerning the nature of the crystalline substrate of the RFH is restricted to only three wells. Two of these (Glamsbjerg and Grinsted) are located in Jutland, whilst the third (Per-1) is located on the shoulder of the Tail End Graben near the western limit of the RFH (figure 2.1). The onshore wells reached T.D in medium-grade metamorphic rocks dated by the K/Ar method at 825±15 Ma (Glamsbjerg), and 880±15 Ma (Grinsted) (Ziegler,1982). These dates are broadly comparable to those obtained from samples taken from the Dalslandides of Southern Norway (e.g Watson, 1976), and the Precambrian basement of Southern Jutland is therefore usually correlated with that of Southern Norway and regarded as part of Baltica (Watson,1976; Ziegler,1982; Pegrum,1984a,b; Brochwicz-Lewinski,1984).

The basement composition of the offshore sector of the RFH is even less well constrained than the onshore sector. The sole direct sample of the crystalline basement is the Per-1 well, which reached T.D in a microgranite dated by the K/Ar method at 435 Ma.(Ziegler,1982). This well has only recently been released into the public domain, and it is not known whether this Caledonian age refers to a cooling age for the granite, or whether it is a metamorphic re-setting of an older basement unit. Ziegler(1982) notes that an Ar/Ar dating of this core yielded a "Scourian" age of 2400 Ma, but in the absence of accompanying details on the petrography of the sample, and the level of alteration, these results should be regarded with caution.

Frost et al.(1981) compiled the relatively few well samples of crystalline basement in the North Sea and adjacent areas, and from a combination of published radiometric age determinations and original petrographic analysis, constructed a schematic basement province map of the North Sea (figure 2.1). This construction is comparable to Ziegler's

(1982) Caledonian framework, and portrays the Caledonian deformation front curving on an arcuate trajectory through the RFH so that the Mid European "branch" of the Caledonides link with their Scottish-Norwegian counterparts (figures 2.1 and 4.20). These authors note the difficulties of making a reconstruction from isolated and scattered well control points, and in drawing a firm boundary corresponding to the proposed deformation front accept that some of the control wells may have sampled allochthonous basement thrust sheets in external zones which may be over 100 kilometres away from the true position of the crustal province suture. Nevertheless, in subscribing to a fixed plate tectonic interpretation of the 'three armed' Caledonian orogenic system, these authors failed to address the fundamental kinematic aspects of the trilete collisional setting which is implied by their basement reconstruction.

If the radiometric determination of a Caledonian age for the Per-1 sample is accepted as genuine, then it suggests that the westernmost block of the RFH was an integral part of the collisional zone. This further implies that the deformation front must lie somewhere to the east of the well location on the shoulder of the Tail End Graben, and must separate the Precambrian basement onshore from the Caledonian basement of the westernmost block. There is no indication, however, in this new mapping of the basement structure of the RFH, of any arcuate zone of intense basement deformation equivalent to that which might be expected along the contact between the allochthonous Caledonide, and the autochthonous Dalslandide (or Cadomide) crustal domains. This is surprising, particularly when it is considered that there is an almost universal tendency for Caledonide thrust faults to be reactivated as basin bounding normal faults throughout the Upper Palaeozoic and

Mesozoic rift basins of N.W.Europe (see, for example, Dikkers,1977; McClay et al.,1986). Instead, the structural framework of the RFH is dominated by an orthogonal set of major basement faults oriented WNW-ESE and NNE-SSW (figure 4.1). If, as Ziegler(1982) has proposed, the WNW trending arm of the Mid-European Caledonides formed in response to northward subduction and collision, would it not be expected that the suture would be characterised by south verging thrusts, which might subsequently have been reactivated as north-hading normal faults?

The only direct evidence of extensional reactivation of pre-existing compressional basement structures is found along the eastern boundary fault of the southern segment of the Else Graben (figure 4.14). In the previous section it was argued that the suite of west-dipping fault plane reflections emanating from the basement beneath the Else Graben correspond to a pre-existing thrust complex composed of basement shear zones. The Per-1 well is located immediately adjacent to the Else Graben, and provides a direct calibration of the basement provinciality of the crustal thrust complex. On the assumption that the basement sample in Per-1 was accurately dated, it must be concluded that the thrust complex is a Caledonian structure. Furthermore, since no comparable structures have been observed in the basement to the east of the Else Graben, it is concluded that the 'Else Imbricate Zone' corresponds to the Caledonian deformation front (figure 4.22).

The interpretation presented above of a Caledonian thrust complex with a NNE-SSW trend and an easterly vergence is in direct conflict with the reconstructions of Frost et al.(1981) and Ziegler(1982). Moreover, the similarity in strike, vergence and geometry of the southernmost nappes of the Norwegian Caledonides and the inclined shear zones of the

Else Duplex is a compelling argument for there being a southward continuation of the collisional remnants of the Iapetan margin of Baltica in the Central North Sea.

If a common genesis of the NNE trending Southern Norwegian nappes and the NNE trending Else Duplex is accepted, then given the present day positions and orientations of the two areas (figure 4.1), it must be concluded that the two areas were offset from one another during or after the Caledonian deformation. Simply projecting along the NNE-SSW strike (figure 4.23), the net offset is approximately 100 kilometres in a sinistral sense. There is no evidence in the Norwegian Sector for any strike-slip deformation of this magnitude during the Mesozoic, and the Late Variscan strike-slip motion along the Tornquist Zone is generally accepted as having been dextral (Arthaud and Matté,1977). In the absence of any conclusive evidence for a post-Caledonide sinistral offset of the Danish and Norwegian thrust 'fronts' along any obliquely or transversely intersecting wrench or fracture zones, it is concluded that the offset was inherent in the Caledonian orogenic framework.

The conclusion that the offset of the thrust front is primary, as opposed to a later imposed deformation is in close general agreement with the transform concept proposed by Pegrum(1984b) (figure 4.21(A)). Pegrum's reconstruction not only accounts for the enigmatic reversal in subduction and collisional nappe vergence between the Scottish and Norwegian Caledonides, but also provides an explanation for the persistent reactivation of faults along a narrow swath extending from N.Jutland to the Orkney Islands. The reconstruction of the basement framework of the North Sea presented here differs from that proposed by Pegrum(1984a,b), however, in that the transform boundary is viewed here as a much broader zone of sub-parallel roughly WNW-ESE trending crustal

dislocations (c.f figures 4.21(A) and 4.24). Instead of regarding the RFH as a slither of Baltican crust attached to the dominant transform along the Tornquist Zone, it is proposed that the principal transform must lie to the south of the Else Imbricate Zone. The obvious candidate for this transform is the Romo Fracture Zone, which it should also be recalled is the main suture between the Mid-European Caledonides and the Baltic Shield. Brochwicz-Lewinski et al.(1984) also favoured the southern margin of the RFH as the main transform boundary, but whereas they prefer to continue the transform via an offset along the Central Graben to the Southern Uplands Fault, it is considered here that the strong WNW-ESE alignment of the RFZ, the Adda Fault Zone and the 'basement corridor' along the Olaf Fault Zone-Lindesnaes Ridge (Chapter 3.6), instead points to a continuation of the transform boundary beneath the Central Graben (figure 4.25).

The distinction between the various WNW-ESE trending fracture zones as to whether or not they acted as the dominant or only subordinate transform faults during the closure of the Iapetus Ocean is largely semantic. The important point is that the balance of the evidence from the well penetrations of the crystalline basement, the seismic imaging of thrusts in the basement, and the inferences of basement structure made from mapping the products of their later reactivations all cumulatively endorse the notion that one of the three arms of the Caledonide orogenic triple junction was a transform plate boundary. A useful modern analogy for this postulated plate configuration of an intra-continental to intra-oceanic transform boundary is the western indent of the India-Asia collisional front from the Makran to the Pamirs. The deformation along this plate boundary is distributed in a diffuse, almost ductile manner along a broad transect of the colliding

plates (figure 4.26). This N-S alignment of the oceanic transforms and their intra-continental counterparts with elongate slivers of plate fragments sliced off one plate and accreted on to the other plate is reminiscent of the broad zone of sub-parallel shears that cross Denmark and continue into the North Sea (figure 4.24).

Many European geologists from Stille(1924) to Watson(1976) have remarked on the pre-eminence of the NW-SE fault lineament direction in Europe. These lineaments are particularly apparent in outline maps of the Variscan and Caledonian massifs (figure 1.1). They were repeatedly reactivated in several different basin forming phases, and most notably in the Late Carboniferous-Early Permian, provided the conduits for the extensive extrusion of magma. When this family of NW-SE trending vertical crustal lineaments is considered in the light of the Iapetan transform origins of the Tornquist Zone and its sub-parallel shear belt, it is tempting to extend the kinematic framework to include the entire family of lineaments as a suite of Rheic Ocean or Iapetus Ocean transform faults (figure 4.27). Given that the microcontinental massifs are all bounded by these lineaments, is it then conceivable that the extraction, transport and docking of the rifted fragments of Gondwana were ordered along fixed paths by the constraining lines of the parallel transform suite, in a similar fashion, perhaps to the cycle of Africa's donation of microcontinents to Southern Asia during the Mesozoic and Tertiary? It is intriguing to consider in this respect, that the conceptual view of a latitudinal Rheic Ocean dissected by closely spaced latitudinal transform faults and its relationship to the meridional Iapetus Ocean, was almost exactly replicated by the successor Atlantic and Tethyan Oceans (figure 4.28). If, as Watson(1976), suggested, the NW-SE "Randtroge" formed at some stage during the Archaean, and if the

repetitive and recursive role of these lineaments as transform faults for the opening and closing phases of successive Wilson cycles is proved to be correct (figure 4.29), then it may be that far from being passive accommodation structures in the course of plate motions, the lineaments are fundamental, irreversible, and ineradicable elements of the Earth's Mantle.

CHAPTER FIVE: THE LATE PALAEOZOIC AND MESOZOIC EVOLUTION OF THE DANISH NORTH SEA.

5.1 INTRODUCTION.

The aim of this chapter is to draw together the numerous filaments of description and analysis presented in the preceding chapters in an attempt to answer some of the more fundamental questions of basin formation and evolution posed in the previous four chapters. The previous chapters are structured in a partly chronological and partly geographical way, in a format which evolved as a result of differences of emphasis which were forced by variations in the coverage of the basic data. Basin analysis must necessarily be an integrated process, but the volume of description required to reach certain conclusions is such that the material has to be divided arbitrarily into structural and stratigraphic headings. A recurring theme of this thesis is the absolute inter-dependence of tectonics and sedimentation, and the overlaps that exist between chapters two and three are a testament to this relationship. In this final chapter, therefore, it is intended to unify the disparities introduced by the structuring of the thesis. The evolution of the Danish North Sea is addressed in a chronological progression, taking account of the rhythmic subdivision of the stratigraphy into mega-sequences which cover distinct epochs of particular dynamic states. Each section is intended to build from the preceding section in a manner that emphasises the way in which each phase of crustal evolution inherits attributes from preceding phases. Questions posed in one section are often only soluble in succeeding sections once the crucial patterns become distinguishable from chance associations, and these fundamental questions form a thematic core around which each section is constructed.

5.2 EPEIROGENIC PLATFORM SUBSIDENCE: MIDDLE DEVONIAN TO LATE CARBONIFEROUS.

Most previous palaeogeographic reconstructions of the Central North Sea do not consider the Danish Sector to have been an area of active subsidence during the Devonian and Carboniferous. In the major reference text on the North Sea, for example, Ziegler (1982, Enclosures 6 to 11 inclusive) depicts the Danish Sector as part of a persistently elevated block, attached to the Fenno-Scandian massif. The depositional limit of the 'Variscan Foredeep' is often assumed to lie approximately along the line of the Romo Fracture Zone (figure 2.2) although Ziegler(1982) includes a larger portion of the Danish Sector in the foredeep by the Westphalian (figure 5.1).

Dewey(1982) suggested that the RFH developed as a peripheral bulge or continental flexure complementary to, and contingent upon loading of the foredeep by the external thrust sheets of the Variscides in Northern Germany, Holland and Belgium. Dewey(1982) argued that the amplitude and wavelength of the RFH were "about right" for a flexural mechanism, but failed to explain the durability of the uplifting mechanism through the Late Permian, Triassic and Jurassic, when the RFH remained as a stable block set amidst the surrounding subsiding Permian Basins, long after the Variscan nappes had been completely peneplained. The peripheral bulge mechanism also fails to explain the rapidity of the uplift of the RFH in the Late Carboniferous (Chapter 4). Nappe emplacement and thrust loading produce progressive lateral migration of a load driven lithospheric response, rather than the fixed, dramatic domal uplifts and transtensile fracturing observed from the RFH. One of the most diagnostic features of true foreland basins, is that as the thrust load migrates towards the hinterland, the maximum axes of lithospheric

downbending and upward complimentary flexure migrate in tandem, and the younging fill of the foredeep therefore progressively onlaps the margin of the hinterland (Dewey,1982),(figure 5.2).

The results of the reconnaissance mapping (Chapter 4) show that the RFH was part of the Southern North Sea 'foredeep' during the Devonian and Carboniferous. Ziegler(1982) noted that "the definition of the northern depositional margin of the Westphalian foredeep is fraught with major uncertainties caused by its intense truncation during post-Carboniferous times". In spite of this restriction, he concluded that "During the Late Carboniferous, the axis of the foredeep migrated northwards as a consequence of the advancement of the Variscan deformation front." This may certainly be the case for areas of Northern Germany immediately adjacent to the external thrust sheets of the Rheno-Hercynian Zone (Krebs,1976), but can the same foreland basin mechanism adequately explain Devono-Carboniferous basin development in the Southern and Central North Sea?

The outstanding characteristic of the Devono-Carboniferous megasequence as seen in the Danish Sector is the parallelism and continuity of the reflection signature over large distances (Chapter 2.3, Chapter 4). Jump correlations of this megasequence across the Danish Central Graben show an almost loop for loop similarity between the sequence on the Mid North Sea High and the RFH, and from the limited well penetrations on the Mid North Sea High, it was suggested that the megasequence ranges from Middle Devonian to Westphalian (Chapter 2.3). The similarity of the megasequence in the two areas suggests that they formed part of the same basin throughout this period. To the south, this basin encompassed most of the southern North Sea and the borderlands of Northern Germany and Holland (figure 5.3), but how far to

the north this basin extended is not known. Pre-Permian reflectors have been identified beneath the deeply buried fill of the Northern Permian Basin, but the limits of seismic resolution are such that no direct correlation of character can reliably be made with the pre-Permian of the RFH. It is possible that the Devono-Carboniferous megasequence extends beyond the Vinding Fracture Zone to abut against the Fenno-Scandian massif along the Fenno-Scandian Border Zone, and it is interesting to consider the occurrences of Late Carboniferous marine sediments in the Oslo Graben in this context. Alternatively, it should be borne in mind, that in Northern Jutland, the only penetrations of the pre-Permian north of the Vinding Fracture Zone encountered sediments of Early rather than Late Palaeozoic age. This may well indicate that the pre-Permian floor of the Danish-Norwegian Trough is entirely composed of Lower Palaeozoic sediments (figure 5.4). Irrespective of which of these two interpretations is correct, the fact remains that the larger part of the Central and Southern North Sea formed a single basin, and the pattern of subsidence governing the accumulation of sediments over large proportion of this basin resulted in the stratiform type of reflection configurations. This subsidence must therefore have been uniform and horizontal on a scale of hundreds of kilometres. There is no evidence for any internal onlap in the megasequence, and certainly no sign of the progressive northward shift of marginal onlap that would be expected if this basin developed as a true foreland basin. There is little internal faulting to suggest that the crust was being actively extended at this time, and consequently the basin can not be considered as a more diffuse equivalent of the block and basin network of the British Isles. What mechanism is appropriate, therefore, for the development of this basin?

To a Russian stratigrapher, the platform or epeirogenic subsidence of an area the size of the Central and Southern North Sea by approximately 5 kilometres over a period lasting 70 to 80 million years would not be considered in the least unusual (Aleinikov et al.,1982). The vast cratonic massifs of Russia and Siberia provide the best examples of platform subsidence of any of the continents. This experience of craton-scale 'downwarping' has fostered many of what are considered in western eyes to be outlandish hypotheses for basin formation, such as the densification and phase change concepts of Artemjev and Artyushkov (1971). Geographically isolated from the more demonstrably active plate margin processes that occupy the greater proportion of the imagination of western geologists, our Soviet colleagues have been freer to dwell on the dynamics of vertical motions of contintal areas. In a western context, the Devono-Carboniferous subsidence of the North Sea basin defies any explanation. The setting of the basin, at the very core of the Ordovician to Early Devonian consolidation of the peripheral Iapetan landmasses with all the implications thereof for thermal and isostatic disequilibria, should have been ripe for the kind of post-orogenic collapse recently described from the Himalayas (Royden and Burchfiel,1987) and envisaged for other parts of the Caledonian mountain chain (McClay et al.,1986; Enfield and Coward,1987). However, the region simply subsided en masse, seemingly immune to Variscan developments further to the south. The continuity of stratal geometries and the general absence of active extensional faults is evocative of some form of thermal recovery mechanism of subsidence, but it is not at all obvious how uplift and peneplanation of the thickened crust in the Central North Sea could be superceded by a thermal re-equilibration. The normal response to crustal thickening is

thermal re-equilibration. The normal response to crustal thickening is isostatic: the return to an equilibrium of density and, therefore temparature, is achieved through uplift, erosion, creep, convective heat transport (anatexis), gravitational collapse, and metamorphism. The attainment of a final peneplain thus implies isostatic and thermal equilibrium (figure 5.5). All the available evidence points to the establishment of a subdued topography in the Central North Sea by the Early to Middle Devonian (Ziegler,1982), and it is difficult to link any post-Early Devonian thermal decay to a pre-Devonian collisional event. Unless a thermal perturbation is invoked at the beginning of the Devonian, centred on the Southern North Sea, and without any obvious corroborative manifestations in the form of surface vulcanism, it is difficult to imagine how such a thermal mechanism could apply. There is no simple solution here: the limitations of currently available well data prevent the kind of thorough quantitative analysis of the variation of the rate of subsidence with time that might clarify the nature of the driving subsidence. The Russian experience should perhaps be borne in mind, however, when any future consideration of the problem of epierogenic subsidence is attempted.

5.3 MEGASHEARS AND RHOMBOCHASMS.

5.3.1 The Late Carboniferous to Early Permian Initiation of Rifting in N.W.Europe.

In Central and Southern Europe, the Late Carboniferous was a transitional period; a shift in the crescendo of bulk transpression under the 'closing yaws' of a Gondwana-Laurasia convergence to a transtensile fragmentation of the new supercontinent. The protracted overture to full continental separation and ocean basin formation lasted over a hundred million years, but from the point of the dynamics of the continental break-up, it is this first period of rift initiation that is the most informative.

The initiation of rifting in the North Sea was marked by a period of uplift, erosion, and magmatism, and by the development of a major angular unconformity, the Saalian Unconformity (Chapter 4). In the Danish Sector, the platform sequence of Devono-Carboniferous was uplifted and faulted, and the rotated apices of the many fault blocks were intensely truncated. The main axis of uplift was centred on the RFH and the Mid North Sea High, and these central North Sea Highs were themselves broken along the spine of their arches by several approximately N-S trending grabens. The uplift of the RFH was controlled and delimited by two marginal fracture zones, which were transtensionally reactivated splays of the earlier Tornquistian transform system (Chapter 4.3).

The hiatus represented by the Saalian Unconformity is often taken to be Stephanian to Autunian in age (Ziegler,1982). However, the thickness and seismic facies of the early rift-fill sequences lying directly above the unconformity in the STEG (figure 2.9), the Else Graben (figure 4.18), and the Horn Graben (figure 4.11), and their relationship to the overlying Upper Permian are regarded here as indicating a likely Westphalian to Early Permian age range for the initial syn-rift deposits. The deposition of these sediments in the grabens transecting the central highs was coeval in part with the continued uplift and denudation of the highs, and it is probable, therefore, that the age of the hiatus is markedly diachronous over this part of the North Sea. The initial phase of rifting and uplift can, however, be regarded in a loosely defined sense as Late Carboniferous to Early Permian.

The precise timing of the magmatism that accompanied this uplift and fragmentation of the Central North Sea is hampered by the relatively

small number of wells penetrating Late Carboniferous/Early Permian volcanic rocks, and by alteration of the sampled material. Seismic evidence for the relative age of eruptives versus early rift sediments is equivocal, but the limited data suggest that the extrusives 'coated' the irregularly peneplained land surface over some parts of the RFH, and the surface rugosity was then infilled by the lowermost onlapping units of the rift fill. Dixon et al.(1981) suggested that the extrusive rocks are restricted to the stable blocks in a manner comparable to the distribution of flood basalts of the Colorado Plateau, but the aeromagnetic signature and well data point to a close correlation between the main loci of surface activity and the WNW trending fracture zones (figure 5.28; Ziegler,1982). It is considered probable that the major fracture zones bordering the RFH formed the principal conduits for the strongly alkaline magmatism, particularly since the gravity and magnetic anomalies and limited refraction seismic data across these lineaments suggest that they extend through the crust, and possibly well into the upper mantle, conceivably to the lower lithospheric depths implied by the source chemistry of the magmas. In addition, the association of domal uplifts with the axes or polarity reversal zones of several of the transecting grabens may also be connected with the magmatic activity. In the Oslo Rift, the segment boundaries form the loci for alignments of ring complexes (Ramberg and Spjeldnaes,1978), (figure 5.6), and some of the more complex curving fault patterns mapped in the axial zone of the Horn Graben and Else Graben (figures 4.1 and 4.9) may owe their origin to caldera collapse faulting (figure 5.7). This mechanism can also be seen to have occurred along one of the principal segment boundaries in the Rio Grande Rift, the Jemez Lineament (Chapin,1978).

Several important questions remain to be answered, however, as far as the mechanism that governed the magmatism, uplift and rifting is concerned. The mechanism should not only account for the spatial relationship between the rifts, the fracture zones and the axis of uplift, but it should also account for the observations of segmentation in all the rifts that have been described from this area. It is also important to consider the extent to which the fracture pattern was influenced by crustal anisotropy, and how the fracture pattern can be interpreted in a dynamic sense.

The Late Carboniferous to Early Permian tectonic framework was clearly influenced to a high degree by the inherited structure of the Tornquistian transform margin (c.f figures 4.1 and 4.24). The boundary faults of the Southern Else and Southern Tail End Grabens were shown in Chapter 4 to have developed through selective reactivation of inclined shear zones that were interpreted as the correlatives of the Southern Norwegian Caledonian basement thrusts (figures 4.22 and 4.23). This concept of reactivation of basement thrusts offers an explanation for the unusually low angle of inclination of the rift bounding normal faults, and by extrapolation of this argument, the similarly low angle and similarly oriented northern segments of the Coffee Soil Fault would also seem to have formed by this process. The basic framework of the North Sea Rift is thus accounted for entirely by extensional reactivation of the staggered transform-dominated structure of the Central North Sea (figure 4.25). This explains the general features of orientation and inclination of some of the rift elements of the N.W.European area, but does not provide a unifying explanation for other elements such as the Horn and Oslo Grabens.

When N.W.Europe is viewed as a whole, certain features of the Late Carboniferous-Early Permian tectonic framework stand out as being of singular importance (figure 5.8). Firstly, all the rifts or grabens are oriented N-S or NNE-SSW. Secondly, all these rift elements terminate against or intersect with NW-SE or WNW-ESE trending fault lineaments. In the Danish Sector examples of the intersecting relationships are provided by the Tail End and Else Grabens (figure 4.10), and the Horn Graben (figure 4.9), with the Romo and Vinding Fracture Zones. The disposition of the grabens with respect to the broadly NW trending lineaments on the scale indicated in figure 5.8 is strongly suggestive of some form of pull-apart - strike slip relationship. What, then, is the evidence in detail, from mapped structural relationships for the magnitude and sense of this postulated strike-slip and pull-apart motion?

Returning to the Late Carboniferous-early Permian tectonic framework of the Danish Sector, it is clear from figure 4.1 that there is no consistent sense of offset of the graben-bounding faults by the faults associated with either of the two marginal fracture zones. The apparent offset of the W.Horn Fault across the RFZ, for example, is dextral (figure 4.13), but as discussed in Chapter 4.2.2, this offset may simply reflect the mechanical perturbation on the fracture propagation process represented by the underlying presence of the transverse basement dislocation, and need not be a later dextral offset. Similar arguments were applied to the apparent sinistral offset of the Coffee Soil Fault across the Adda Transverse Zone (Chapter 3.4.2). Along strike to the west, the RFZ may terminate at the axial faulted zone separating the two oppositely inclined segments of the Else Graben, or alternatively, it may left-step along the southern segment of the Else

Graben to continue further to the west as the 'pseudo-sinistral' Adda Transverse Zone, in the classic manner of pull-apart to offset wrench interactions (Aydin and Nur,1986). The VFZ is equally enigmatic as regards the detailed nature and sense of the offsetting relationships of the fracture zones and the graben bounding faults.

The lack of any clear through-going fault strands along the trace of the marginal fracture zones necessarily rules out the possibility of there having been any significant horizontal displacement along either the VFZ or the RFZ during the Late Carboniferous-Early Permian tectonic phase, assuming that basement translation of the blocks juxtaposed across the fracture zones was fully coupled to the basement deformation represented in the opening of the N-S trending grabens. However, as argued in Chapter 4.2, the structural style exhibited by the fracture zones is indicative of a transtensile deformation. How, then, can the observations of cross-sectional structural style be reconciled with the constraints imposed by the structural relationships in plan view? In a complex braided system of vertical shear zones such as represented in the North Sea by the Tornquistian splay suite, or for a more thoroughly documented example, the San Andreas network of strike-slip fault in California (e.g.Crowell,1974), the kinematics of slip distribution throughout the network are immensely complex. Recent investigations of the refractions of stress fields in the vicinity of the San Andreas Fault are revealing surprising relationships between stress (as measured in well bore break-outs (Mount and Suppe,1987) and displacement(as measured by geodetic grids (Mason,personal communication) across some of the major and minor strands of the splaying fault system. It is clear that our understanding of the kinematics of networks such as these is

at an elementary level, and the first principles of strike-slip deformation laid down in the 1970's (Harding,1974; Wilcox et al.,1973) may be substantially incorrect. It is quite conceivable, for example, that on the fanning and interconnecting network of Tornquistian splay shears, a bulk shear between the bounding undeformed cratons of Baltica and Gondwana of a particular sense may be distributed on the network in combinations of different sense motions. Much would depend on the geometry of the intersections of the splay shears at depth and along strike, and on local variations of crustal strength. The lensoid crustal blocks bounded by the splays might break down along inherent flaws in order to facilitate any minor rotations that would be induced by variations in frictional coupling along the length of the splay shears, and depending on how displacement gradients were maintained along the vertical fault surfaces, the adjacent blocks may rotate in unison or in opposition(figure 5.9).

This kinematic/dynamic regime would certainly explain the inconsistency of the sense of offset observed along portions of the marginal fracture zones of the RFH (figure 4.1). When gross slip vectors for the transecting graben segments are plotted on the tectonic framework map (figure 5.10), it becomes possible to imagine just such a system of differentially rotating, rhombohedral basement massifs bounded by discontinuous, splaying bounding shears as described above, and as exemplified by areas such as the California borderlands. The magnitude of the horizontal translations necessary to satisfy the rotations implied by the extension on the transecting rifts (the pull-aparts at the block corners) need only be of the order of 10-15 kilometres. Any larger displacements, if coupled to the brittle upper crust, would have breached the left and right stepping offsets, have formed continuous fault traces, and have resulted in intense permeated fracturing of the

cover sequences over broad zones. Since none of these phenomena have been observed, it is concluded that the total distributed transtensile shear across the RFH must have been less than 30 kilometres.

Previous regional syntheses of the Late Carboniferous and Early Permian structural evolution of N.W.Europe (Arthaud and Matté,1977; Ziegler,1982) invoke considerable dextral horizontal translation along a suite of NW-SE trending lineaments forming a continental megashear crossing Central and Southern Europe, transforming the convergent motion on the Uralides and Mauretanides (figure 5.11). Arthaud and Matté (1977) suggested that the translation across fault lineaments such as the Biscay-North Pyrenean Fault, the High Atlas-Chedabucto Fault and the Elbe Line were of the order of 100 to 200 kilometres, and more recently, Pegrum(1984a) has suggested the possibility of a 350 kilometre dextral offset across the Tornquist Zone. Smaller dextral wrench components (10-25 kilometres) are well constrained by offsets of Late Variscan granites along splays of the Armorican Shear Zone (Arthaud and Matté,1977), whereas the much larger wrench motions invoked for the NW-SE "first-order wrench faults" seem to be based on 'offsets' of structural markers such as the Variscan deformation front, which may not necessarily have been initially contiguous in the first place. Arthaud and Matté(1977) made the important observation that many small Westphalian basins in France were of the pull-apart type, and they described in detail how local grabens with often thick accumulations of coal measures formed at the terminations of the primary and conjugate fault lineaments. They extended their appraisal of the pull-apart grabens to include the Oslo and North Sea Rifts, complementing the work of Dikkers (1977), who pioneered the technique of lineament analysis as applied to the rift fabric of N.W.Europe.

The principal difficulty with the idea that the NW-SE suite of lineaments were sites of major dextral strike-slip motion during the Late Carboniferous and Early Permian, is that most of these fault lineaments are embedded entirely within the continental lithosphere. The tips of at least one end of the fault lineaments are contained entirely within the continent (figure 5.12). This requires that certain mechanical principles of the relationship of fault length and displacement distribution on the fault surface be observed, in the same way as on any scale of contained dislocation. This differs from transform faults in a true plate tectonic sense, that simply translate plate motions from one plate margin or boundary to the next, and where motion is conserved by constructive or destructive plate margin processes (figure 5.13). Where a plate boundary transform passes into an intra-continental transform, the differential motion imparted at the plate boundary must be dissipated by combinations of brittle and ductile strains before the tip of the fault is reached (figure 5.12). A displacement gradient is likely to exist along the entire length of the intra-continental transform fault, in a comparable manner to that recently described for normal fault systems by Barnett et al.(1987). Whilst fairly large strike-slip displacements could accrue near to the plate boundary, it seems unlikely that these would be communicated deep into the interior of the plate. Instead, it might be predicted from simple mechanical considerations, that the large displacement would be progressively taken up by brittle and ductile shortening and extension, conjugate splay wrenching, and rotation of a fairly broad transect of the continental lithosphere in the vicinity of the lineament (figure 5.14). The precise manner in which each of these strains would be distributed would depend on factors such as strain rate, geometry of the

transform lineament, lateral variation in mechanical properties of the non-rigid continental lithosphere, and degree of coupling at the plate margins.

Opinions differ as to the most probable extreme westward limit for the Tornquist Zone. Ziegler(1982) favoured a termination at the intersection with the Oslo Rift, but Pegrum(1984a,b) suggested that the Tornquist Zone extends along fault lineaments in the southern Norwegian Sector, and continues via the Outer Moray Firth Basin and the Wyville-Thomson Ridge to the coast of Greenland. This latter reconstruction is preferred here, since it offers a plausible means for linking the rifting in the Norwegian-Greenland Sea to that in the North Sea. The distribution of active Late Carboniferous-Early Permian rifts and NW-SE lineaments is illustrated in figure 5.8, where the pull-apart relationship of the rifts to the lineaments is immediately apparent. All the lineaments terminate at or close to rifts, although the terminations of the Pays de Bray-North Rockall Trough Lineament and the Biscay-North Pyrenean Fault are not well constrained. The cluster of small grabens in the Irish Sea and Solway Firth, and the Cheshire Basin-Worcester Graben pair can be regarded as a series of pull-aparts linking a sidestep in the Pays de Bray-North Rockall Trough Lineament.

The tip of the Tornquist Zone is shown on figure 5.8 to be immediately to the west of the southern segment of the Norwegian-Greenland Rift. There is no evidence of any activity along strike from this position on the mainland of Greenland, although it should be borne in mind that the projected continuation of the Tornquist Zone on Greenland would be along a major Proterozoic mobile belt, the Nagssuqotidian Belt (Pegrum,1984a). Assuming, therefore, that the active limit of the Tornquist Zone was at the intersection with the

Norwegian/Greenland Rift, then from the previous discussion of the distribution and dissipation of displacement along an intra-continental transform fault (figure 5.14), it is clear that if large strike-slip displacements are invoked along the Polish sector of the Tornquist Zone, then there must have been a complimentary dispersal of this motion along those sectors leading to the 'fault tip'. From figure 5.14, it is conceivable that the distributed strain is expressed in the splaying of the main Tornquist strand into the fanning suite of lineaments crossing the North Sea, and in the development of the pull-apart basins at local termini or bifurcations of the individual splays. Small scale rotations of fault bounded blocks are common in splaying strike-slip systems (Nur et al.,1986), and the earlier inference of minor rotation of the rhombohedral massifs of the RFH accords well with this regional setting of the termination of a major intra-continental transform fault.

The cumulative extension on all the pull-apart rifts connected to the splaying Tornquist network should give an approximate upper limit for the total strike-slip motion along the main strand of the Tornquist Zone further to the east, providing that the upper crust is coupled to the lower crust and upper mantle. With this assumption, and by summing the heaves on the major Late Carboniferous-Early Permian rift-bounding faults measured parallel to the splay lineaments, it is estimated that the maximum dextral translation along the Tornquist Zone in Northern Europe was of the order of 50 to 100 kilometres. In conclusion, therefore, whilst the recent mapping and interpretation of fracture patterns of the North Sea is in keeping with the central hypothesis of distributed dextral shear and pull apart fragmentation outlined by Arthaud and Matté(1977), a more conservative estimate of the strike-slip displacements on some of the first order lineaments is

preferred. The initial opening of the North Sea Rift is thus seen to have resulted from the distribution of the bulk dextral shear over the dispersed suite of splay faults which formed the terminal sector of the Tornquist Zone.

The strike-slip and pull-apart mechanism for initial rifting described above for the Late Carboniferous and Early Permian of N.W.Europe is not generally considered in modern treatments of the processes of continental rifting (e.g Morgan and Ramberg,1987). The term **pull-apart basin** is usually restricted to small rifts that develop at step overs along major strike-slip faults, where the long axis of the basin is parallel to the strike-slip faults. Although this sense of the term was coined first in the early 1970's, the fundamental concept of rifting by differential shear between sub-parallel lineaments was originally proposed by Carey(1958). Carey's rhombochasms and megashears were the foundations for a hypothesis that depicted continental deformation as a continuum which passed from features which would be classed as pull-aparts in modern terminology, through continental rifts, to fully formed ocean basins (figure 5.15). Continental rifts whose long axes were across the strike of the bounding megashears were, in this scheme, simply an ensemble of rhombohedral pull-aparts, and the passage from continental rifting to ocean basin formation was merely an extension of the mechanical framework of the rhombochasms and the megashears. Wilson's transform faults are the essence of Carey's megashears, but restricted to the oceanic domain. It is appropriate, then, that the long dormant Iapetan transforms were resurrected in a continental setting in the Late Carboniferous to form the megashears for this overture of continental rifting that was to culminate in full oceanic separation in the Mesozoic. The Iapetan transforms were reactivated initially as intra-continental strike-slip faults, but then

in keeping with the progression envisaged by Carey, developed into the oceanic transform faults for the Atlantic Ocean. In this way, the Wilson cycle was repeated under the controlling framework of the original transform megashears.

5.3.2 Wrench Induced Rifting: the mechanical significance of segmentation and the rôle of magmatism.

The main argument presented in the previous section in favour of a wrench induced mechanism for the Late Carboniferous-Early Permian initiation of rifting in N.W.Europe was the spatial relationship of the rifts with the NW trending continental lineaments. The rift elements could be viewed as 'pull-aparts' because of their diminutive areal extent relative to the length scale of the lineaments. Crucial to this mechanism of rift initiation is the idea that the crust is torn under an applied torsional force, rather than under a balanced, evenly distributed tensional force. A simple demonstration of this mechanism can be made by taking a piece of paper, and first attempting to pull it apart from opposing sides, and then attempting to tear it apart by 'pinning' one corner (figure 5.16). The pulling method results in frustration, but under a comparatively mild torque, the paper develops a tear which propagates into the interior of the sheet. The resulting tear is invariably jagged, and significantly, the rate of tear propagation is found to be sporadic. The 'crack' advances in steps, locking at each successive jagged position until it leaps on at a single move to the next locking point. This type of crack propagation is well documented from the materials science literature, where the phenomenon is known as crack blunting (Atkinson,1987). The incremental propagation is usually the result of the presence of defects in the deforming medium, and although this is only fully described on the scale of a crystal lattice,

there is no mechanical reason why this same phenomenon should not also apply at crustal scales. The principles of fracture propagation have been successfully applied to the development of jumping spreading centres in oceanic rifts (Hey and Duennebier,1984; Pollard and Aydin,1984). Courtillot(1982) formulated a model of rifts propagating under an evenly applied tension which addressed the effects of "blocking zones" of higher strength material on the rate of longitudinal propagation (figure 5.17), but the basic elements of the mechanics of crack growth have not as yet been applied to studies of the fracture patterns of continental rifts.

The simple experiment with the piece of paper showed that if a crack is thought to have propagated under a torque (anti-plane shear or tearing mode in fracture mechanics terms(Atkinson,1987)), then several important features should be apparent (figure 5.18):-

(1) The crack should have a V shape in plan view.

(2) There should be a diachroneity of deformation along the axis, younging towards the tip of the crack.

(3) The edges of the crack could well be jagged, and the notches would be related to defects in the material.

(4) Jumps in the propagation of the crack should show spatial relationships with any pre-existing defects in the material.

Two continental rifts that are sufficiently well known to allow the accurate determination of the key parameters of fracture patterns and timing of deformation, and which both appear to satisfy all the above conditions are the Oslo Rift and the Rio Grande Rift. In both cases, the rifts are V-shaped in plan view (figures 5.19 and 5.20), and the narrowing is achieved through a step-wise reduction in the width along the axis in a number of discrete segments. The narrowing towards the tip

is accompanied by an incremental reduction in the total upper crustal extension as measured across the axis of the rifts (Ramberg and Spjeldnaes,1978; Chapin,1978). In both the Oslo Rift and the Rio Grande Rift, there is a northward diachroneity in the timing of eruption and cooling of the initial basaltic magmatism associated with the early opening of the rift. It is virtually impossible to date precisely the onset of initial rupture in an absolute sense. The first accumulation of syn-rift deposits, for example, may lag behind the actual establishment of an active border fault by several millions of years, depending on factors such as climate, topography, and magnitude of vertical motion. Similarly, the eruption of magma at surface is dependent not only on the availability of conduits for the ascent of the magma, which may or may not be the rift bounding fractures, but also on the plumbing at deeper levels in the crust, and it cannot therefore simply be assumed that there is a prima facie relationship between magma extrusion and rift propagation. Nevertheless, in the absence of any other plausible means of dating the fracture initiation, the evidence of diachroneity in the onset of magmatism can be taken as a reasonable indication of diachroneity in the gross fracture propagation, particularly when there is also evidence of longitudinal variation in the chemistry of the first erupted lavas, as is the case in both these rifts.

Ramberg and Spjeldnaes(1978) made the important observation in the Oslo Rift, that the various stages of doming, fissure eruption, central volcano and caldera development, and major batholith emplacement "did not occur simultaneously along the entire length of the graben, but in general...occurred progressively later from the SSW to the NNE". In addition, they noted that there were significant differences in the degree of chemical evolution of the basalts on a segment by segment

basis along the axis of the rift, from the primary, undersaturated derivatives of the Skien stratified series, through the basanites of the central area, to a single tholeiitic flow in the north, on the Krokskogen Plateau.

A similar northward diachroneity in the initial eruptive magmatism has also been described by Chapin(1978) for the Rio Grande Rift, where the resolution of the radiometric age determinations is much tighter because of the relatively recent formation of the rift. Chapin(1978) also noted that the age progression occurred by segments, with the initial magmatism in the wide southern segment at 32 m.y B.P, and in the northern segment at 27 m.y. B.P.(figure 5.20). Taking these dates as an approximate index of the onset of fracture propagation, the averaged rate of axial propagation was about 10 cm./yr. This figure is of a comparable magnitude to the reconstructed plate motion vectors for the western U.S.A for the Oligocene (Chapin,1978). In addition to the diachroneity in opening, there is a northward reduction in width and total extension measured across the rift. This reduction is manifested in decreasing numbers of individual fault bounded basins per segment, with the clear implication being that the segmented structure was the prime factor in the overall accumulation of incremental extension.

To summarise thus far, it is concluded that both the Oslo Rift and the Rio Grande Rift, which evolved in contrasting plate tectonic settings at different times, exhibit many of the characteristics that would be predicted for a propagating tear fracture. In both cases, the importance of the segmented structure of the rifts is evidenced by the staggered way in which the rifts appear to have propagated, and by the spatial, temporal, and geochemical relationship of the segments and the extrusive magmatism. Furthermore, both these rifts terminate at their

open, southern ends against major continental lineaments; the Oslo Rift against the Fjerritslev Fault (figure 4.23), and the Rio Grande Rift against the Texas Lineament (figure 5.21, Carey,1976). Both these lineaments are thought to have been the locus for dextral horizontal translation at the time of rift propagation, and therefore satisfy the remaining condition for a megashear bounding the initial opening point of the tear.

The question now remains as to the exact function of the segmentation in the initial propagation of this kind of wrench induced tear rifting. In the Oslo Rift and the Rio Grande Rift, the segment boundaries follow the alignment of pre-existing lines of weakness in the continental lithosphere. In the Oslo Rift, the NW trend of the segment bounding Oslofjord Fault, for example, and the NNE trend of the oppositely inclined Akershus and Ringerike-Vestfold Grabens in the Oslo Rift are both represented in the adjoining Precambrian massifs, as is a third, less important NE trend (figure 5.19). The incipient rift thus would have had a variety of options for 'easy' fracture reactivation, but the important point for understanding the mechanics of the opening of the rift, is not that the fracture pattern is a relict of pre-existing lines of weakness, but rather that certain orientations were reactivated in different senses in preference to others. In the Rio Grande Rift, a similar range of orientations of pre-existing lines of potential failure existed in the basement prior to rift initiation, but the final fracture pattern is very markedly segmented on an overall NNE-SSW axis, by a combination of N-S trending basin bounding faults and acutely intersecting NE-SW trending segment bounding fault zones (figure 5.20). This NE-SW orientation would seem to be unfavourably acute with

respect to the rift-bounding faults, since an ideal intersection would be much closer to 90 degrees (Gibbs,1984). However, the NE-SW anisotropy is represented by a set of shear zones in the Precambrian shoulders of the rift which separate regions of different age and composition. It is probable, therefore, that the fundamental nature of these basement province boundaries allowed the mechanical disadvantages of acute orientation to be overridden. Rift-related magmatic centres are aligned along these NE-SW trending lineaments in the Precambrian shoulders for distances up to several hundred kilometres away from the rift axis (Cartwright,1988b), which suggests that they were tectonically active far beyond the limits required in the simple passive mode of reactivation often depicted for such transverse structures in rifts (Gibbs,1984; Illies,1981; Bally,1981). The distribution of the deeply sourced magmas along the segment bounding lineaments instead supports Chapin's(1978) suggestion that they have a more fundamental rOle.

The presence of pre-existing lines of weakness in the continental lithosphere expressed in the form of mobile belts or shear zones is analagous to the presence of defects or dislocations on the microscopic scale of crack growth. It is suggested, therefore, that in wrench induced tear rifting of the type envisaged for the evolution of the Rio Grande and Oslo Rifts, the initial point of rupture would nucleate on the megashear bounding edge, at some pre-existing 'defect' (figure 5.22A). For each increment of added wrench displacement imparted by the bounding megashear, the rift would propagate a certain amount into the interior of the undeformed continental massif, exploiting to the full those elements of the basement anisotropy that were energetically favourable. The rift would propagate in this way relatively

instantaneously, until it met a buttress (figure 5.22B). This might be any fundamental fault or shear zone or lithological contrast. Deep seated continental lineaments such as the NE-SW trending shear zones of the Rio Grande Rift might be oriented at a large range of acute angles to the overall rift axis and still fulfill this 'crack blunting' rÔle. At this point of blunting, the rift would lock, and additional increments of wrench displacement would be converted into continued extension on the single rift segment (figure 5.22C). The buttressing lineament or segment boundary would also propagate into the previously undeformed rift shoulders as this extension proceeded. At this stage, magma generation would probably be confined to the initial segment.

The locking of the rift under the continuously applied boundary torque would increase the elastic strain in the area surrounding the blunted end (Atkinson,1987). Eventually, sufficient potential energy would be invested in the elastically deformed region for the buttressing effect of the lineament to be overcome. At this point, the rift would jump across the lineament, and rupture on a second segment would be initiated (figure 5.22D). The first segment would then continue to extend along with the second segment, but not necessarily at the same rate. Any differential extension between the two segments would be taken up along the first segment boundary in oblique or wrench motions. Meanwhile, the advance of the second segment of the propagating rift would be blocked, perhaps, by a second intersecting lineament or 'defect', and the 'crack' would again be blunted. Magma generation might migrate at this stage into the second segment, but in the time taken for the rift to breach the first buttress, the first-formed partial melts might have evolved to more saturated varieties. This would be manifested

in a segmented pattern in the bulk chemistry of the extrusive magmas, comparable to that reported by Ramberg and Spjeldnaes(1978). The build up of 'magmatic pressure' during the period of locking, without the facility to tap large volumes along the rift bounding fractures would lead to preferential generation, migration and extrusion of magma for considerable distances along the actively propagating transform lineaments. Such a process could be regarded as the continental analogue of leaky oceanic transform fault magmatism (Garfunkel,1986), and offers an explanation for the distribution of volcanic centres along the NE-SW trending lineaments in the Rio Grande Rift. The process of segment addition, enlargement and migration would continue for as long as the torque was applied, and the final configuration of the rift and the distribution of the magmatism associated with the rifting would record the number of incremental steps in the initial propagation (figure 5.22E).

The mechanical model presented above was for the idealised case of a single continental block and a single bounding megashear. In reality, continental rifts are often pseudo-linear structures composed in detail of numerous individual rift elements: the North Sea and East African Rifts are typical in this respect (Cartwright,1988b, figure 1). In the North Sea, the suite of NW-SE trending continental lineaments are distributed over a large area, and the many inter-connections with potential failure lines offered a host of different ways in which the bulk dextral shear could be distributed. In detail, the morphology of the individual rift elements does bear a close resemblance to that of the generalised model (figure 5.8). The bi-polar forms of the Horn Graben and the Else Graben (figure 4.1), can each be visualised as being composed of two V-shaped segments, that widen outwards to bounding

megashears (the fracture zones bounding the RFH) (figure 5.23). The Viking and Horda Grabens (figure 5.8) narrow northwards, and are bounded to the south by the major strand of the Tornquist Zone (Pegrum,1984a). The Danish and Dutch Central Grabens narrow to the south away from the distorted and distended rhombohedra of the kinked intersection zone in the Danish Sector. Unfortunately, there is little constraint on the timing of opening of any of these rift elements, but given their morphological resemblance to the type examples of wrench-induced rifts, and their relationship to the continental lineaments, it is probable that their morphology is a direct result of this mode of initiation.

5.3.3 Rotational Components in Global Tectonics.

Segment boundaries are regarded as crucial elements of the tectonic and magmatic evolution of the class of wrench-induced rifts described above. Many of the features of the Rio Grande and Oslo Rifts that are satisfactorily accounted for in this mechanical model are also observed in many other continental rifts. The observation that magmatic centres are often aligned along the transverse lineaments rather than along the rift-bounding faults is equally as valid for the East African, Rhine, Baikal and North Sea Rifts as it is for the Rio Grande Rift. In the North Sea Rift, for example, the volcanic centres of the Forties area, and on Texel, off the Dutch mainland, are both located at the intersections of transverse continental lineaments (Pegrum,1984a). The model also accounts for the ubiquitous development of a segmented morphology in spite of the great variation of local anisotropy (Cartwright,1988b), for the step-like nature of rift margins, for longitudinal variation in amounts of extension, for minor strike-slip motions along segment boundaries and for the spatial arrangement of the rifts relative to intersecting continental lineaments. This wider

occurrence of features regarded as diagnostic of tear-like propagation raises the possibility that Carey's Rhombochasm and Megashear concept may be an appropriate basis from which to approach the genesis of continental rifts in general.

A similar system of intra-continental wrench faults connecting disparate rift elements has been invoked by Katz(1987) for the East African Rift (figure 5.24).The spatial dependence of the detailed arrangement of linear elements of the bifurcating and anastomosing sectors of the rift on pre-existing basement trends has long been appreciated (Gregory,1896; Wayland,1921; Holmes,1965; McConnell,1972), but there is an equal or even greater dependence on transversely intersecting mobile zones, shear zones and sutures. The system of intra-continental transform faults proposed by Katz(1987) is appealing in two respects. Firstly, it marries well with the distribution of anomalous magmatic centres such as the carbonatites of Tanzania and the prevalent kimberlites of the craton bounding mobile belts of South Africa. Secondly, it offers a plausible, though speculative means of viewing the development of the East African Rift as no more than a continuation of the fragmentation of eastern Gondwana along a suite of guiding megashears (figure 5.25). One of the most interesting aspects of Katz's lineament analysis is that one of his more prominent lineaments, the Walvis Bay-Mombasa-Mogadishu Lineament (figure 5.24) connects a first-order (large offset) oceanic transform fault in the Atlantic Ocean to one in the Indian Ocean (figure 5.26). This lineament has had a long history of 'plate boundary' activity dating back to the Proterozoic (Daly,1986), but it seems doubtful that plate tectonic concepts could account for the ocean-continent-ocean link depicted in figure 5.26.

Continental rifting is intrinsic to plate dispersal, but for tectonicists biased towards solutions of two-dimensional balances of force (e.g. Bott,1982), or one-dimensional conduction of heat, little account is taken of the three-dimensional configurations of ancient continental lineaments, oceanic transform faults and continental rifts. Mechanisms for rifting that involve the horizontal transmission of tensile stresses generated at subduction zones (the trench-suck force of Forsyth and Uyeda,1975) are incapable of explaining the origins of intra-continental rifts like the East African Rift, where the continent is virtually surrounded by constructive plate boundaries. Similarly, advocates of passive lithospheric stretching invariably fail to identify the source of the "passive tensile stress field" responsible for the stretching, nor do they document the means by which these stress fields are transmitted for great distances across highly anisotropic continental lithosphere in such a way as to maintain an often remarkably uniform crustal extensional response for many millions of years. Active mechanisms of rifting are almost certainly applicable in certain cases, particularly when doming over a large radius and widespread magmatism accompany the rifting, but it is highly unlikely that every major continental rift was initiated in response to penetrative mantle diapirism.

The mechanism addressed in the preceding discussion, of large scale dissemination of relatively minor horizontal translation along inter-connecting networks of lithospheric or tectospheric lineaments, offers an explanation for the three-dimensional distribution and morphology of intra-continental rifts located at large distances from the nearest plate boundaries. It obviates the difficulties of stress transmission, and relies instead on physical translation, and it

circumvents the problems presented by amagmatic rifts for the mantle plume model. The outstanding problem with the wrench-induced mechanism is what precisely causes the minor differential shearing on a continental scale?

In the search for a causative basis for the megashear mechanism, three simple observations need to be taken into account. Firstly, the ancient continental lineaments that appear to be durable elements of the megashear framework are helical (Carey,1958; O'Driscoll,1980; Wezel,1988), and are biased towards the equator. The largest offset transform faults of the planet, for example, are located within the tropical zones of latitude in the Pacific and Atlantic Oceans. Secondly, most major rifts or spreading axes are meridional. Thirdly, phases of widespread rifting, vulcanism and relative high stands of sea level alternate in a cyclical manner with phases of orogeny and relative low stands of sea level (Milanovsky, 1978).

The first two observations lead naturally to thoughts of rotation: the equatorial bias points to a relationship between tectonism and angular velocity (Carey,1976). The main argument opposing a rotational component in the motor of plate motions is that the viscosity of the mantle is too high for the rate of rotation to have any significant effect (Jeffreys,1970, p.452). In spite of this physical objection, the geological appeal of a rotational component is immediate to any observer who compares satellite pictures of the atmosphere with bathymetric charts of the oceans. The similarities in the vortices of the tropical storm patterns to the oroclinal eddies at the lee of the large continental masses are so profound as to warrant a closer look at meteorology from a tectonic perspective; Wegener's inter-disciplinary journey in reverse.

Several recent attempts have been made to re-kindle interest in rotational effects on tectonics. Gilliland(1973) drew an analogy between zonal rotation on Jupiter, the Sun and Saturn, where large scale shearing of the differentially rotating fluid bodies is observed along the zonal boundaries, and the distribution of oceanic transform faults on Earth. Nelson and Temple(1972) speculated that there is an east flowing mantle 'jet stream' at low latitudes, which might explain differences in the inclination of Benioff Zones at the western and eastern margins of the Pacific Ocean. Gilliland(1973) stated "if any part of the mantle is fluid-like in its behaviour as is patently conceded by those who believe in convection, and if variation in angular velocities is common to rotating, spherical, fluid bodies, then such variation may exist in the motion of the fluid-like part of the mantle." If the complexities of an externally heated, convecting and rotating fluid system like the Earth's atmosphere are any guide as to the complexities that might be expected from an internally and externally heated rotating and convecting fluid like the mantle, then we should not expect to find order and cyclic repeatability in the patterns of surface response to the internal engine. However, just as weather prediction depends on certain dependable and recurrent parameters, then conceivably the mantle fluid system may have a memory for certain conditions, and the cyclic element of plate tectonics may be a clue to this memory. The monsoon, for example, is bound to occur every year, because of the relationship of the atmosphere to the present day distribution of land masses. Could there be an equivalent condition in the mantle fluid system, whereby for given conditions of continental distribution on the Earth, instabilities in rotation would be induced, and break-up and dispersal, or convergence and orogeny would be the dominant tectonic

mode?

Wezel(1988) has argued for a cyclic variation in rotation rate to explain cyclic variation in rifting, vulcanism, and absolute sea level. He cited the work of Mörner(1986) on the influence of rotation rate on the latitudinal distribution of seismicity, in support of a mechanism that relates phases of rifting, high heat flow , vulcanism and high sea level to periods of acceleration of rotation and bulging of mass at the equator, and phases of orogeny, subduction and low sea level to periods of deceleration in rotation and elongation about the equator. This cyclicity, which is so evident in global charts of relative sea level change (Vail et al.,1977), was regarded by Milanovsky (1978) as evidence of alternating phases of minor contraction and expansion of the Earth. Sheridan (1983) has extended the notion of pulsation (see also Van Bemmelen,1972) to incorporate a correlation between periods of low magnetic flux (magnetic quiet zones) and periods of acceleration in mid ocean ridge accretion. Sheridan envisages a coupling between the outer core and lower mantle, whereby mantle plumes are generated in greater abundance during periods of rapid turn-over in the outer core dynamo.

The conflict here, in moving towards the concept of a rotational influence on surface tectonics, is similar in some respects to the conflict between the empirical and the theoretical, the geologist and the thermodynamicist, Geikie and Kelvin. The objection to rotation is based on modern measurements or estimates of the viscosity of the mantle, but how appropriate are these for the periods of active rifting, extensive flood vulcanism, and high global heat production? Is it conceivable that during these periods, the viscosity of a significant proportion of the mantle is reduced below a point at which the Earth's

rotation would have a significant impulse on patterns of mantle flow? If a rotational flow stream was operative at certain periods of high thermal activity, how would this be expressed in the patterns of surface tectonism? If there is an analogy with the zonal rotation of other planets (Gilliland,1973), then it might be reasonable to expect sub-latitudinal torsion of the kind described for the Tethyan Shear Belt by Carey(1958), and for this to be expressed in the motions and dispersal patterns of the continental plates.

Apparent polar wander paths contain a code that might help to unravel a possible rotational component in absolute plate motions. A cursory glance at APW's for the Late Palaeozoic and Mesozoic (Smith et al,1980) shows that the continents move in zig-zag paths relative to one another. Africa, for example, relative to Europe and N.America, swung to the north-west in the 'Variscan', and then to the east in the Mesozoic, and then curved back towards the north-west in the Cenozoic. Is this tacking motion a more general phenomenon?

The arguments presented earlier in this Chapter, and at the end of Chapter 4, concerning the durability of the tectospheric lineaments come to the surface again in connection with this possibility of oscillatory tacking of the continents. Carey(1958) advocated a rhegmatic shear pattern as a fundamental component of the planetary structure, and this has been echoed by O'Driscoll(1980) and Wezel(1988). Bryan(1987) compared this possible lineament network on the Earth, with tectonic lineament patterns on the other terrestrial planets, and argued that if we are to appreciate the significance of the lineament patterns on our own planet, then we must compare and contrast the tectonic patterns of the Earth with those of other planets. If such a system of helical, conjugate NW and NE trending lineaments was present in the upper mantle, would it not be reasonable to expect a rotationally forced phase of

plate motions to be dictated by the tectonic grid? The tacking motions could be envisaged as a 'Rubik's spheroid', where the range of possible motions was pre-determined by the helical lineaments. Transforms inherited from one generation of continental fragmentation would be ideally oriented under a later rotational resurgence, to convert changes in angular momentum into plate motions during a new phase of separation and dispersal. The influence of rotation discussed here is, of course, highly speculative. Nevertheless, the longevity of continental lineaments such as the Tornquist Zone or the Walvis-Mombasa Line is perhaps a point of observational departure for a more studious re-examination of the extraneous field of observations that do not readily conform to conventional notions of plate tectonics on a fixed volume Earth.

5.4 DECOMPRESSION MELTING ALONG MAJOR CONTINENTAL LINEAMENTS: PULL-APARTS IN THE LOWER LITHOSPHERE.

The phase of minor dextral torsion and pull-apart formation in the Late Carboniferous and Early Permian of N.W.Europe was followed by the formation of two large E-W trending axes of slow, regional subsidence known as the Northern and Southern Permian Basins. The framework of these two basins was influenced considerably by the WNW and NW trending lineaments transecting N.W.Europe (figure 5.27). Regional subsidence persisted in the two basins from the Late Permian to the Late Cretaceous, although there was a progressive shift of emphasis from the dominance of the NW lineament network, to that of the Mesozoic exploitation of the earlier rift bounding fault systems, as can be seen for example in the Triassic isopach map of the North Sea area (figure 2.20).

The superposition of this system of regionally subsiding elongate basins over the sector of the Tornquist Zone that had previously been a locus for a major phase of extrusive magmatism leads directly to the supposition that the subsidence was produced by thermal relaxation of the lithosphere following a heating event of unspecified origin. This mechanism of relaxation of a lithospheric thermal anomaly was invoked by Ziegler(1982) to explain the development of the N.German Basin and its relationship to the Late Carboniferous and Early Permian volcanic centres. If this mechanism was also responsible for the development of the two Permian basins in their entirety, it would require that the temperature of the lithosphere was elevated along axes which correspond to the axes of maximum regional subsidence.

In lithospheric stretching models of sedimentary basin formation involving pure shear, the axis of the thermal relaxation subsidence is invariably illustrated as being located directly above the axis of the upper crustal extension. The concentric Tertiary gross isopach of the North Sea Basin is often cited as a type example of this kind of thermal relaxation effect (McKenzie,1978), and in a crude sense, there is a spatial overlap between the axis of the underlying rift (and crustal thinning), and the gross accumulation of post-rift sediments. However, more detailed compilations of the sequence isopachs in the Tertiary reveal a far more complex pattern of subsidence and basin fill (Nielsen et al.,1986), and this pattern of Tertiary subsidence may owe as much to the contemporaneous uplifts of Scandinavia and Britain as to the inferred cooling of a lithospheric thermal anomaly. Primary thickness variations resulting from gross basin floor subsidence are difficult to establish in the two Permian basins, since there are complicating influences arising from halokinesis or Late Cretaceous inversion and

erosion. In addition, the regional subsidence was accompanied by continued extension on the N-S trending rift-bounding faults, which resulted in large local departures from the smoother generalised regional thickness trends. It is nonetheless clear, from a comparison of restored Rotliegend and Triassic isopachs with the map of Late Carboniferous to Early Permian tectonic elements (figures 2.11, 2.20 and 5.8), that no straightforward superposition of axes of crustal extension and thermal relaxation can be demonstrated for the period most likely to include such a relaxation. This suggests that either the crustal extension was not accompanied by lithospheric attenuation, or thermal relaxation was not an active process. Furthermore, the comparison of the isopach and tectonic elements maps offers no immediate explanation for the preferential adoption of E-W elongate axes of the regionally subsiding basins, especially when it is recalled that there was little N-S oriented surface extension (Chapter 4, figure 4.1). If a lithospheric stretching mechanism is applied in a strict sense, it is difficult to explain why the Oslo Rift and the Horn Graben, which both have large positive residual gravity anomalies indicative of massive lower crustal attenuation, failed to develop subsequently as centres of thermal relaxation. This failure to respond in the manner predicted by the model suggests that some other form of compensation for the excess mass must have applied.

Faced with the inadequacies of mechanical stretching of the lithosphere as a driving mechanism for the formation of the E-W trending Permian Basins, what other possible mechanism can be invoked that accounts for the spatial relationship of the surface manifestation of a thermal anomaly, and the subsequent regional subsidence? The location

of the main centres of Late Carboniferous and Early Permian vulcanism (figure 5.28) appears to be strongly influenced by the network of NW trending lineaments (figure 5.8). The alkaline, undersaturated geochemistry of the eruptives is indicative of deeply sourced, rapidly emplaced magmas, with little opportunity for crustal residence and contamination (Dixon et al.,1981). If the previous suggestion that these lineaments penetrate the entire lithosphere is correct (Chapter 4), and if, as argued earlier in this Chapter, the likely horizontal translation across these lineaments during the Late Carboniferous and Early Permian was of the order of 20-30 kilometres, then is it conceivable that the generation and migration of the deeply sourced magma was the result of the strike-slip deformation, rather than active or passive lithospheric attenuation? It is plausible that the narrowly defined lineaments at surface would be represented as more diffuse braided networks of shear zone in the mantle (figure 5.29). It follows from this braided geometry, that during phases of strike slip motion along the lithospheric lineament, slip mght be concentrated along certain shear zone branches in preference to others, leaving pods of the lower lithosphere stranded as zones of relative dilation, rather like the pressure shadows developed in association with rigid inclusions in ductile shear zones (Ramsey and Huber, 1987). The formation of dilated pods might be likened to the development of pull-apart basins on releasing bends on upper crustal portions of strike-slip faults, save that under the high confining pressures of the lower lithosphere, voids would not be sustained as such, and the dilation would be expressed instead as a decompression. Under these conditions of constant temperature decompression, partial melting could occur, the volume of melt being a function of the volume of the pod, and the degree of dilation.

Frictional heating and the easy access of deeply migrating volatiles would also have an influence on the degree of melting, and on the chemistry of the magma fraction. The dilatant shear zones would provide an ideal conduit for the rapid ascent of the melt generated within the bounds of the shear zone network, and these would either erupt direct at surface, underplate the crust, or possibly intrude in the lower-middle crust as sill shaped magma chambers (figure 5.30). The voids required to accommodate such crustal magma chambers might conceivably be provided by the intensely fractured zones formed at the intersection of the vertical shear zones and the rift-bounding basement faults. A mid-crustal magma chamber with the geometry of a sill has been identified from deep reflection seismic data from the Rio Grande Rift (Brown et al.1979), and it is significant in the context of this discussion that this magma chamber is located immediately adjacent to one of the NE trending shear zones identified by Chapin(1978). If large volumes of melt were generated in this way, and only a small fraction of the primary derivatives were erupted at surface, as appears to be the case in the Oslo Rift (Ramberg and Spjeldnaes,1978), then underplated magmas could reside as large residual bodies in a semi-fluid state for a considerable period in the areas adjacent to the shear zone conduits (figure 5.30). These underplated bodies would represent an additional load on the lithosphere, which would increase as the magma cooled to a crystalline state. The rate of cooling would be a function of the thickness of the magma bodies (Turcotte and Schubert, 1982) and the level of heat flux from below. The relatively slow cooling of a large volume of underplated magma, emplaced beneath the Permian Basins might, therefore induce a regional, load driven subsidence of the form observed for these basins.

No attempt is made here to quantify such a process of adiabatic decompression melting on a continental lineament of lithospheric dimensions, and clearly the test of such a hypothetical mechanism must come from a more rigorous volumetric analysis of the kinetics of the melt generation. A further test might be to examine the distribution of sheared peridotite xenoliths erupted in alkaline continental basalts, to see if there was any preferential distribution along deep continental fractures. It would also be instructive to compile rare earth and noble gas characteristics of magmas derived in proximity to lineaments and compare those abundances with those found in magmas erupted at some considerable distance from any obvious lineament conduit.

As a postscript to this discussion of the possible rôle of shear-generated magmas in contributing to the subsidence of the Permian Basins, it is interesting to note that few geometrically oriented studies of extensional tectonics address the rOle of magma generated during the extension on the mechanical aspects of the extension. Gibbs(1984), for example, argued forcefully for a listric detachment model for extensional fault systems, and disregarded alternative geometries such as planar domino block faulting (Morton and Black,1975), or symmetric conjugate normal faulting (the keystone block configuration)(Horsfield,1980) on the grounds that these geometries introduce unacceptable space problems at depth (see also Bally,1981). Yet it seems entirely reasonable, that in a dynamic system in which magma generation and migration play a fundamental part, 'space problems' would be valuable adjuncts to the magmatic plumbing in the lower crust. Most rift vulcanism is bimodal, and this clearly requires that differentiation and contamination of mantle-derived mafic primary melts occurs in the lower and middle crust. Since assimilation of crustal

material must be limited volumetrically by the isotopic and bulk chemical constraints of the silicic end members of the erupted lavas and pyroclastic rocks, it follows that part of the volume represented by the crustal magma chambers must come from space created by physical extension of the crust(figure 5.39). Orton(1988) has documented a dependent relationship between palaeogeography, the amount of surface uplift and subsidence, and the volume of large pyroclastic eruptions in a Middle Ordovician rift, and this points to just such a delicate balance between extensional deformation and magma emplacement and eruption.

5.5 SYMMETRIC AND ASYMMETRIC RIFTING IN THE DANISH CENTRAL GRABEN: DEEP CRUSTAL STRUCTURE AND THE EXTENSIONAL STRENGTH OF THE CRUST.

5.5.1 Introduction: two phase rifting in the Mesozoic.

The Mesozoic evolution of the Tail End Graben can be divided into two distinct phases of fault controlled subsidence. The first phase is represented in the stratigraphy of the graben fill as the Permo-Triassic megasequence, and the second phase is represented by the Middle and Upper Jurassic megasequence. The two phases were separated by a tectonic lull in the Early Jurassic, when no appreciable subsidence occurred in the graben, and no appreciable uplift occurred on the adjoining flanks. This tectonic hiatus is marked in a stratigraphic sense by a prominent sequence boundary which is generally concordant to the sequence layering above and below (Chapter 2.6).

The term megasequence refers to a grouping of sequences that may differ in detail individually, but collectively share the same bulk characteristics, by virtue of the fact that they were deposited under a genetically consistent set of dynamic conditions. An example of this usage would be the equivalence of the Devono-Carboniferous megasequence as observed on the RFH, to the Permo-Triassic megasequence of the

Southern Permian Basin. In both cases, the megasequences are characterised by uniformity and parallelism of reflection configurations over large areas, and these in turn are related to a regional (cratonic) driving subsidence. Megasequences are not formally defined as such, but could be regarded as a higher order stratigraphic division than the second order cycles of Vail et al.(1977).

The two phases of Mesozoic rifting have markedly contrasting stratigraphic and structural expression in the Tail End Graben. The first phase was marked by a dominance of the NNW-SSE trending fault set and by parallel reflection configurations. These configurations require that the graben floor subsided horizontally, and it appears to have achieved this by synchronous faulting of the Coffee Soil Fault together with antithetic and synthetic step faults dispersed over a wide area and bordering to the west against the Mid North Sea High (figure 2.22). There was only a subtle influence of the transverse fault elements, recognisable, for example, in gentle longitudinal variation in the total thickness of the Triassic (Enclosure 7) and in the distribution of the mobile Zechstein evaporites (figure 2.15). In contrast, the second phase was marked by a progressive increase in the influence of the WNW-ESE trending fault grain, by a narrowing of the width of the graben to the confines of the fulcrum of the Jens-Otto Fault Zone and the Coffee Soil Fault, and most significantly by a wholesale shift towards a rotational style of subsidence. This rotation was achieved through a massive increase in the displacement rate on the Coffee Soil Fault (Chapter 3.3, figure 3.18). The aim of this final section is to attempt to explain the contrast between these two phases of rift controlled subsidence in a manner that is consistent with the detailed observations presented in Chapters 2 and 3.

5.5.2 The Deep Crustal Structure of the Danish Central Graben.

The only constraints on the deeper structure of the rift in the Danish Sector come from Seasat altimetry derived and ship-borne derived gravity data. The results of a recent modelling (Holliger,1987) of these data is presented in figure 5.31(Holliger,1987). Constraints on the shallow crustal structure were obtained from depth-converted conventional seismic data, and information on sediment densities was obtained from density logs of Danish Sector wells. Holliger(1987) made a series of two-dimensional crustal models along lines close to ship tracks. Figure 5.31 is one of these lines and crosses the Tail End Graben at its deepest point, in the Northern Tail End Graben. The free air anomaly is approximately zero across the graben (figure 5.31a), which suggests that the graben is almost fully compensated. However, the residual anomaly (calculated by subtracting a calculated free air anomaly assuming no crustal thinning from the observed free air anomaly) is approximately 120 milligals. This was interpreted by Holliger(1987) as evidence of a shallowing of the Moho from a depth of 30 kilometres beneath the shoulders, to 20 kilometres beneath the axis of the graben (figure 5.31b).

This interpretation of crustal thinning assumes a constant crustal density of 2.8 g/cc and a constant upper mantle density of 3.3 g/cc. Numerous studies of the crustal and upper mantle velocity and density structure beneath continental rifts show that rather than being an abrupt boundary, the contact between the lower crust and upper mantle is transitional in nature, with lower crustal velocities and densities higher than normal, and upper mantle densities and velocities lower than normal (Ramberg and Spjeldnaes,1978; Ramberg and Morgan,1987; Illies, 1981). Although there is clearly a problem of resolution associated with

the gravity modelling which is emphasised by the comparison with the results of integrated geophysical techniques in other rifts, the modelling of Holliger(1987) gives a good first approximation to the deep crustal structure. There can be little doubt that the residual positive anomaly of the wavelength and amplitude computed by Holliger represents a large anomalous mass in the lower crust, but does this signify the intrusion of an asthenospheric diapir (c.f Illies,1981), ductile stretching of the lower crust and lithospheric mantle (c.f.McKenzie, 1978), or whole lithospheric simple shear (Wernicke,1985)?

Similar degrees of crustal attenuation to that inferred for the Tail End Graben by Holliger(1987) have also been reported from the Viking and Central Grabens, either by direct observational techniques such as refraction and deep reflection seismic profiling (Barton,1985; Beach et al.,1987), or by inference, from studies of the thermal subsidence curves derived from backstripping of wells (Barton and Wood,1984). One of the major problems in attempting to apply lithospheric stretching models to explain the evolution of the North Sea Rift, is the large difference between observed values of upper crustal extension measured from conventional seismic data, and those calculated from fitting the reconstructed thermal decay curves to theoretical curves calculated for a range of stretching factors. It is possible to explain this discrepancy in several ways; by invoking hitherto unseen low angle normal faults, which would not be imaged by the seismic data (Barton and Wood,1984), by appealing to the simplicity of the initial model, by invoking some new process of crustal attenuation not accounted for by the initial model (Ziegler,1982), or by invoking a more sophisticated variant of the initial model (Coward,1986; Beach et al.,1986).

The improved resolution of lower crustal structure obtained by deep reflection seismic profiling offers an opportunity to resolve the discrepancies in both the basic data on crustal attenuation, and on the possible mechanisms giving rise to that attenuation. A deep seismic reflection profile across the Viking Graben, for example, shows the lower crust to be transected by numerous faults which have normal offsets as measured from the disposition of the lower crustal layering (figure 5.32). The base of the reflective layering is generally taken to be the Moho (Barton and Wood,1984; Cheadle et al.,1987), and it seems probable, therefore, that the lower crust beneath the axis of the Viking Graben is thinned by normal faults that continue into the upper Mantle. Beach et al.,(1987) interpreted these faults as late strike-slip faults (figure 5.33), but he presented no evidence to support the notion that late stage horizontal translation occurred along the axis of the Viking Graben. On the contrary, structural analyses of the Viking Graben invariably favour a simple extensional development (e,g Threllfall, 1981). An alternative interpretation, therefore, is that the lower crustal faults are continuations of the upper crustal faults, and the crustal structure is composed of several closely spaced planar normal faults cutting the whole of the crust in a domino fault style (figure 5.34). The obvious test to examine whether the crustal domino faulting could account for all the crustal thinning implied by the shallowing of the Moho beneath the Viking Graben would be to calculate the extension from the sum of the heaves of the faults and match this figure against the area loss of the crystalline basement before and after extension (Gibbs,1984). This approach assumes that the Moho is invariant as a structural marker, but as argued previously, where rifting is accompanied by magmatism, considerable changes can occur at the

crust/mantle boundary, and these must surely affect the vertical position of the geophysical Moho. From a detailed study of xenoliths erupted in rift-related extrusives in Australia, Griffin and O'Reilly(1987) have argued that in cratonic areas that have undergone one or more phases of magmatism, the geophysical Moho and the crust/mantle boundary are unlikely to coincide. For rifts with a protracted history of extension with even sporadic evidence of surface magmatism, such as the Viking Graben or the Tail End Graben, the use of the reflection Moho as a marker for the extensional deformation must be viewed as inappropriate.

The possibility that major normal faults bounding rift basins extend through the whole of the crust and continue into the upper mantle, rather than soling out into a ductile lower crust as is commonly assumed in the listric fault model (Bally,1981), is strengthened by deep seismic profiling of numerous Mesozoic rift basins on the U.K continental shelf (Cheadle et al.,1987). On many of the BIRPS profiles, the major boundary faults of the dominantly asymmetric basins extend to the base of the crust, and offset the reflection Moho. In several examples, it is probable that the rift basins developed by extensional reactivation of pre-existing thrusts or shear zones. A well documented example of this relationship is the Outer Isles Thrust, which can be seen to offset the Moho on the MOIST line, and which was reactivated to form the Minch Fault (Peddy,1984). Discrete fault plane reflections have been identified from the lower crust and upper mantle on many of the BIRPS lines (Cheadle et al.,1987), in the case of the Flannan Thrust to a depth of over 80 kilometres. The geometry of rift bounding faults constrained by fault plane reflections are invariably planar, and dip between 30 and 40 degrees. No conclusive examples of listric normal

faults have been demonstrated on the deep reflection data.

The conventional seismic over the Tail End Graben constrains the geometry of the Coffee Soil Fault to a depth of approximately 12 kilometres, and depth conversion (Enclosure 22) shows this geometry to be planar, with dips in the range 30 to 40 degrees. The similarity between the upper crustal geometry of the Coffee Soil Fault and the rift-bounding faults imaged by BIRPS raises the possibility that the Coffee Soil Fault also shares the same lower crustal geometry. This idea is particularly appealing when it is considered that the amount of normal displacement on the Coffee Soil Fault far exceeds that of most other rift-bounding normal faults, and must approach the upper limit of normal offset sustainable by a crustal normal fault. This large displacement carries certain mechanical implications which make the interpretation of a fault plane cutting through the entire crust almost a necessity. If the fault were to terminate in the lower crust, soling out on a sub-horizontal detachment (figure 5.35b), the displacement gradient along the portion of the fault surface with the smallest radius of curvature would be too large to permit the rapid rates of displacement documented for the Late Jurassic (figure 3.18). If the fault continued as a planar feature into the upper mantle (figure 5.35a), then the large displacement could be distributed over a large surface area without requiring a large displacement gradient and the large accompanying ductile strains.

When the crustal model proposed by Holliger(1987) is superimposed on both the listric and the planar interpretations of the structure of the Tail End Graben (figure 5.36), it can be seen that the planar interpretation offers a simple geometric relationship between upper and

lower crustal thinning, whereas the listric interpretation requires that there be a steady-state position for the detachment whilst the crust/mantle boundary is elevated by nearly 10 kilometres. It is considered that this is unrealistic (see England and Jackson,1987), and consequently the planar interpretation is preferred here as the more likely crustal configuration.

5.5.3 Strain Rates, Pre-existing Fractures and the Extensional Strength of Continental Lithosphere.

Recent modelling of the extensional strength of the lithosphere is based mainly on experimental data of mineral assemblages which are taken to be most representative for the upper and lower crust and the upper mantle (Kusznir and Park,1987; Lynch and Morgan,1987). These models predict the relative strength of levels with different rheology under varying conditions of strain rate and heat flow (figure 5.37). However, as White et al.,(1986) have noted, the strength profile of a highly anisotropic crust or lithosphere is likely to be strongly influenced by the mechanical properties of the weakest element of the deforming medium. The observation that many of the rift-bounding faults on the U.K continental shelf developed by extensional reactivation of pre-existing failure surfaces emphasises the validity of White's observation, and given the likelihood that the Coffee Soil Fault also originated by the reactivation of an earlier thrust fault (Chapter 4), the same caveat should also apply in a discussion of the behaviour of the lithosphere in the Danish Sector.

None of the existing models of the extensional strength of the lithosphere takes into account the influence of major planes of weakness. Nevertheless, the distinction between the Permo-Triasic and the Middle-Late Jurassic phases of rifting in the Danish Central Graben

can be understood by reference to these models, providing some qualifications are introduced for the presence of a major inclined plane of potential failure, the antecedent of the Coffee Soil Fault. Kusznir and Park(1987) predicted that for low strain rates and moderate heat flow, extension would be distributed over a wide area, but brittle deformation would be confined to the upper crust. This prediction matches the observation of widely dispersed extension on synthetic and antithetic faults for the slowly subsiding Permo-Triassic phase. Under the low strain rates implied by the displacement/age plot of figure 3.18, and under the waning heat flow conditions that probably prevailed throughout this period, it seems improbable that the rheological distinctions between the upper and lower crust would be subordinate in influence to the mechanical incongruity of the portion of the shear zone contained within the ductile deformation field, and consequently it might be expected that only the upper crustal portion of the fault would be reactivated in a brittle sense (figure 5.38).

For high strain rates and moderate to low values of heat flow, Kusznir and Park(1987) predicted that the brittle zones, which under lower strain rates were confined to the upper crust or uppermost lithospheric mantle, would encompass the lower crust and lower lithosphere, such that whole lithosphere failure might occur. This extreme condition requires much higher strain rates than appear to be indicated for the Middle-Late Jurassic by the reconstruction of displacement(figure 3.18). However, considering that these predictions do not include the effect of the inclined shear zone, it is then conceivable that the acceleration in strain rate observed in this second phase of rifting was sufficient to initiate a brittle reactivation of this shear zone over the entire thickness of the crust. The propagation

of a brittle reactivant would satisfy the mechanical arguments concerning displacement gradients, and the change from symmetric to asymmetric rifting would then be explained as a form of yield behaviour. The balance of the reactivation would not shift to the asymmetry inherent to the crustal fabric until a threshold value of strain rate was exceeded. Once the full extent of the old shear zone became activated as a brittle rupture, any externally driven extension would much more easily fall prey to the compounding influences of sediment loading of the hanging wall.

In conclusion, therefore, the contrasts between the two phases of Mesozoic rifting in the Danish Central Graben are attributed to the different impact that a major crustal scale mechanical discontinuity exerts on the strength of the lithosphere under varying conditions of strain rate and heat flow. Crustal attenuation was achieved principally by simple shear of the entire crust, on the Coffee Soil Fault (figure 5.38).

5.6 CONCLUSIONS.

The most important conclusions of this thesis are summarised as follows:-

(1) The Danish Central Graben is a zone of rift intersection and re-orientation between the NW-SE trending U.K/Norwegian Central Graben and the N-S trending Dutch Central Graben. It is composed of a mosaic of rhombohedral fault bounded blocks, which were formed by combinations of basement normal faults with a dominant NNW trend, and transverse fault zones with a dominant WNW trend.

(2) The re-orientation of the rift axis in the Danish Sector was achieved by incremental and abrupt changes in strike of the major rift-bounding fault, the Coffee Soil Fault, and the conjugate, hinged

margin. These abrupt changes occur at positions where transverse fault zones intersect the rift margins, and the intersections of the two fault trends are marked by intense local fracturing of the rift-fill sequences.

(3) The transverse fault zones served to segment both of the major graben elements, but in contrasting ways. The Tail End Graben is segmented along its axis, whereas the Feda Graben is segmented parallel to its axis. The mechanics of the segmentation also differ, the distribution of displacement along the length of the Coffee Soil Fault was ordered in response to the along-strike segmentation of the fault plane, but no such condition applied in the Feda Graben. Instead, the Gert Ridge functioned as a hinge zone, allowing the free rotation of the two opposing rift-bounding faults.

(4) The segmented fracture pattern exerted a profound influence on the stratigraphy of the rift-fill sequences. This influence was minimal in the Permo-Triassic, during a relatively slow, steady phase of fault controlled, symmetrical subsidence, but became progressively more important during the Middle and Upper Jurassic phase of accelerating asymmetric subsidence. Differential rotation towards the Coffee Soil Fault on the individual graben segments was expressed in torsional motion components along the transverse segment boundaries, and the most pronounced contrasts in subsidence style resulted in the development of structural and stratigraphic hinge zones. These hinge zones formed the structurally controlled loci for the shelf-slope break in the Late Jurassic.

(5) The transverse fault zones were also important in controlling the distribution of fault-scarp related fan depositional systems along the Coffee Soil Fault. Mounded and lobate depositional forms observed from

the Upper Jurassic sequence adjacent to the fault plane, are preferentially located at points of transverse fault zone intersection. (6) Active rifting ceased towards the end of the Jurassic, but the acceleration of the Late Jurassic rifting had outpaced the sediment supply, and a deep marine basin was left extant at the time that fault displacement came to an end. The Early Cretaceous was a period dominated by shallowing onlap basin fill. Remnant fault scarps were onlapped and ponded, condensed sequences accumulated in hollows on the adjoining basement highs. Regional subsidence of the rift shoulders commenced in the Santonian, post-dating the cessation of active rifting of the basement by nearly 50 million years. This rules out the possibility that the regional subsidence of the rift shoulders was a simple response to a mechanical thinning of the lithosphere at the time of initial rifting; the lag time is too large.

(6) The contrast between the horizontal and rotational subsidence patterns of the Permo-Triassic and the Jurassic is explained by reference to the inherent mechanical anisotropy of the crust, and the differing influence this has under varying conditions of strain rate and heat flow. The Permo-Triassic is envisaged as a time when extension proceeded under conditions of waning heat flow and low strain rate, and it is considered that these conditions favoured the development of widely dispersed and shallow brittle extensional faults. The mechanical anisotropy represented by the antecedent of the Coffee Soil Fault would, under these conditions, have been subordinate to the rheological stratification of the crust and upper mantle. Under higher strain rates, the influence of the anisotropic crustal structure was much greater, and extension was concentrated in an asymmetric way on the Coffee Soil Fault.

(7) Crustal anisotropy was the single most influential factor in the protracted basin development of the North Sea area. In the Danish Sector, this influence is seen primarily in the structural fabric of the RFH, where WNW trending lineaments control the margins of the high and those of the adjoining Permo-Triassic basins. These WNW trending lineaments are considered to be significant elements of a broad network of splaying shear zones collectively termed the Tornquist Zone. The antiquity of this major tectonic zone is astounding, as is its durability and repeated pre-eminence in successive epochs of ocean formation, closure and re-opening. The Danish Sector lay on a transform margin during the opening of the Iapetus Ocean, on a transform margin during the closure of the Iapetus Ocean, on an intra-continental transform zone during the 'Variscan Cycle', and on the continental extension of an oceanic transform during the opening of the North Atlantic Ocean.

(8) The zig-zag appearance of the North Sea Rift is seen here as a simple consequence of this transform dominated basement structure of the Central North Sea. In the Late Carboniferous and Early Permian phase of initial rift formation in N.W.Europe, the old transform lineaments were reactivated under a minor dextral torque, and old basement thrusts and shear zones were reactivated as bounding faults to small pull-apart rift basins. The segmentation observed in these pull-apart rifts was instilled in the rift fabric as part of the process of staggered fracture propagation, under the guiding control of the network of intersecting lineaments. In the Danish Sector, the Coffee Soil Fault and the Else Graben bounding fault developed by the reactivation of Caledonian basement thrusts which are considered to be the southerly continuation of the east-verging Norwegian Caledonides. The WNW trending

transverse fault zones that exerted such a strong control on the later rift development in the Danish Central Graben developed as complimentary reactivants of the Caledonian transform lineaments.

(9) A review of the fracture patterns in continental rifts shows that many rifts have a segmented structure. This is attributed to a process of initial rift propagation, where rifts propagate in a step-like manner, and where the steps are related to locking points at the intersection of the potential failure planes with transversely oriented continental lineaments. The formation of segments records the incremental stages in 'crack growth' under a wrench-induced tearing moment. The spatial and temporal distribution of magmatic activity accompanying the early development of many rifts shows a close correlation with the positions of the intersecting continental lineaments. This relationship is taken to signify a far more critical rôle for the lineaments in the process of continental rifting than hitherto conceived, and raises the possibility that continental fragmentation is constrained to follow paths prescribed by the arrangement of ancient continental lithospheric lineaments on a global scale.

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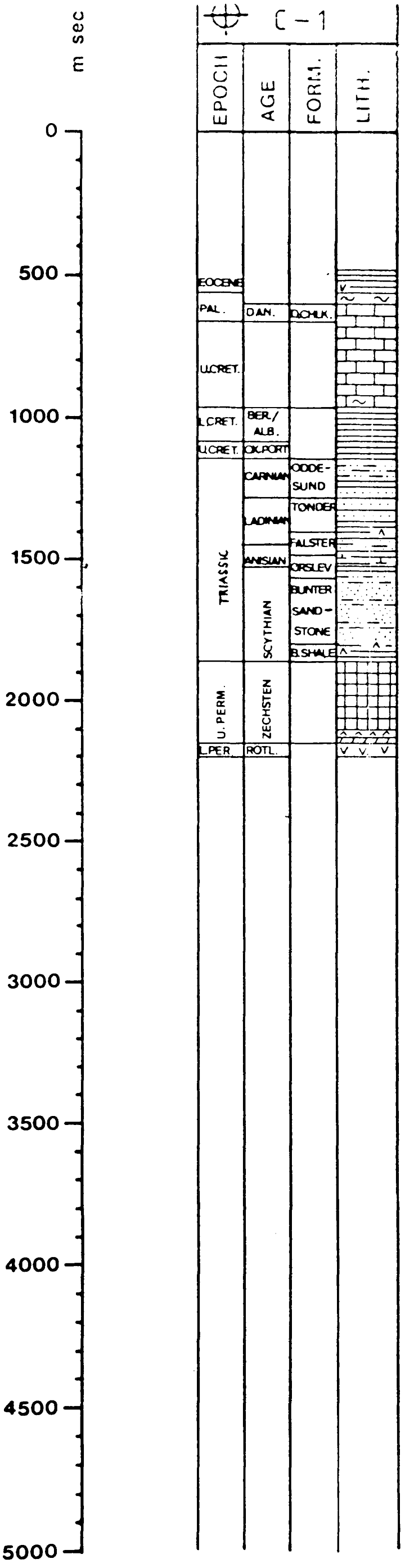
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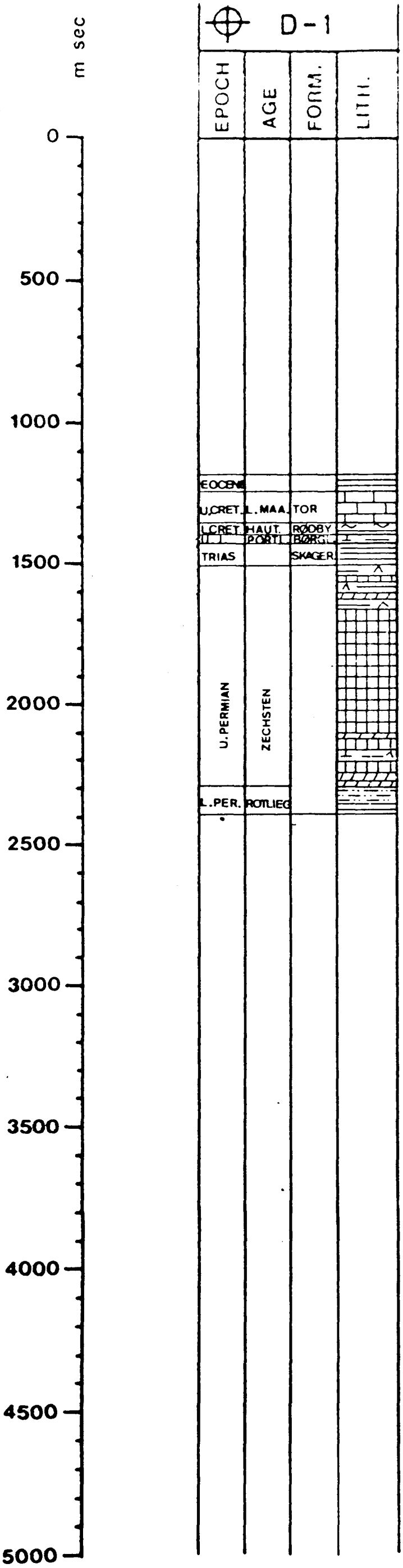
APPENDIX A.

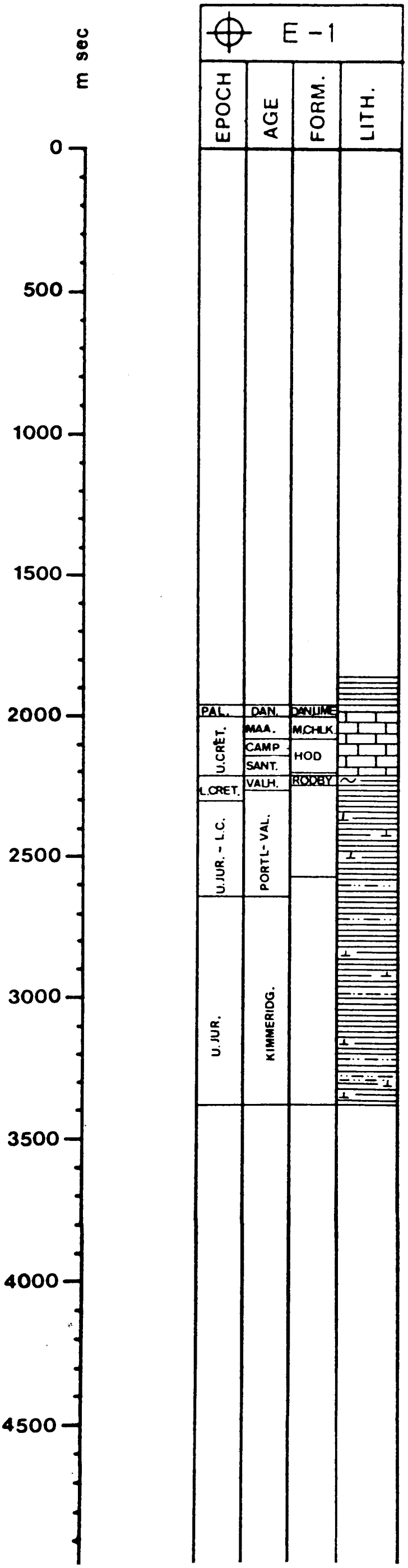
STRATIGRAPHIC SUMMARY SHEETS OF SOME KEY DANISH WELLS.

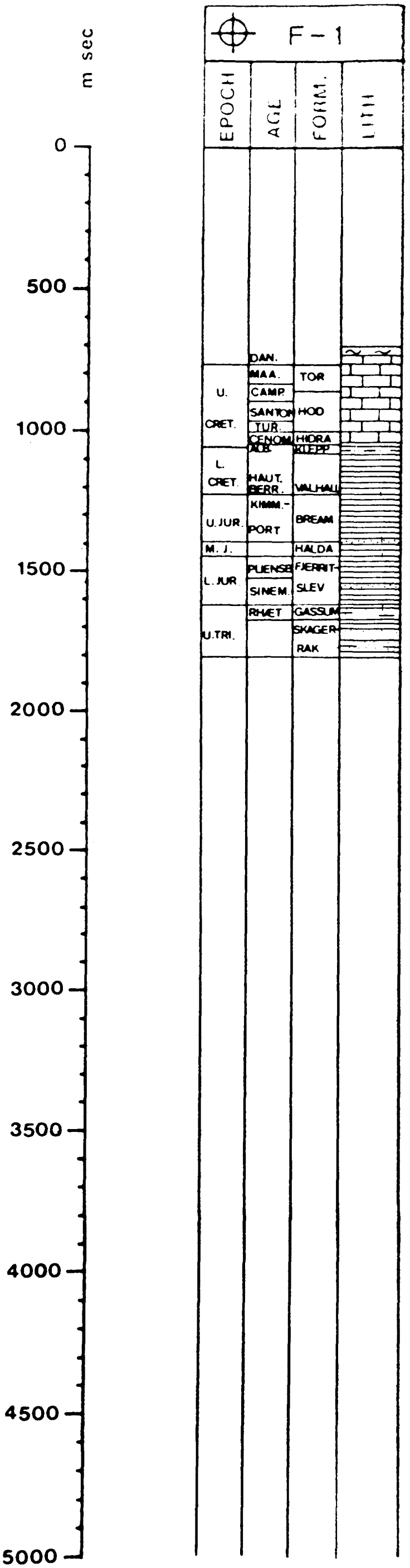
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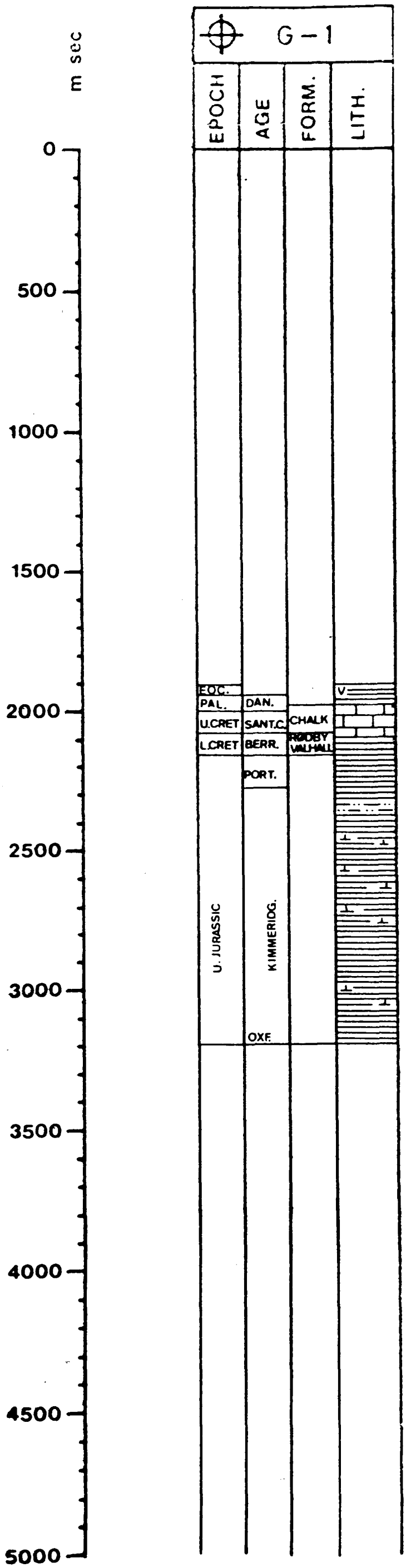
C-1, D-1, E-1, F-1, G-1, I-1, J-1, K-1, L-1, M-8, O-1, P-1, Q-1, R-1, S-1, U-1, V-1. The ages, lithostratigraphic terminology, and lithologies are summarised for each well, and displayed in one-way time (milliseconds). The information is taken from the operator's reports.

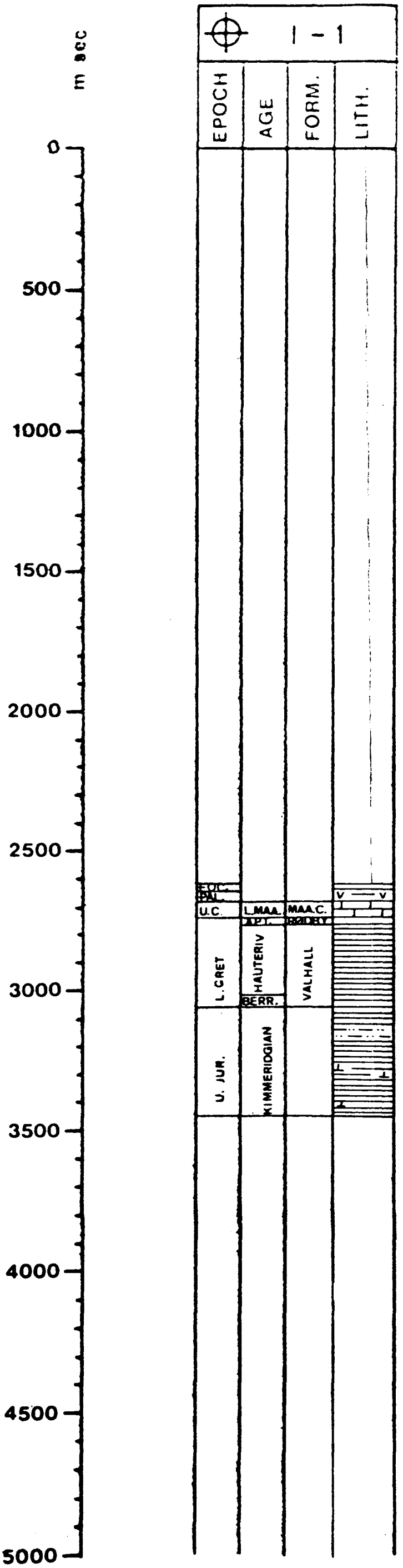

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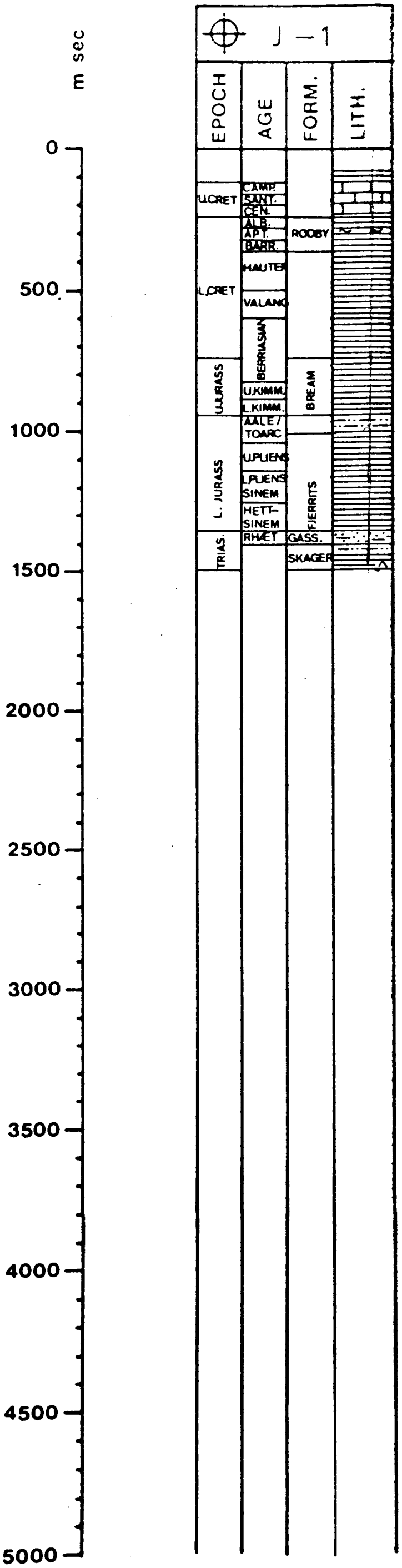

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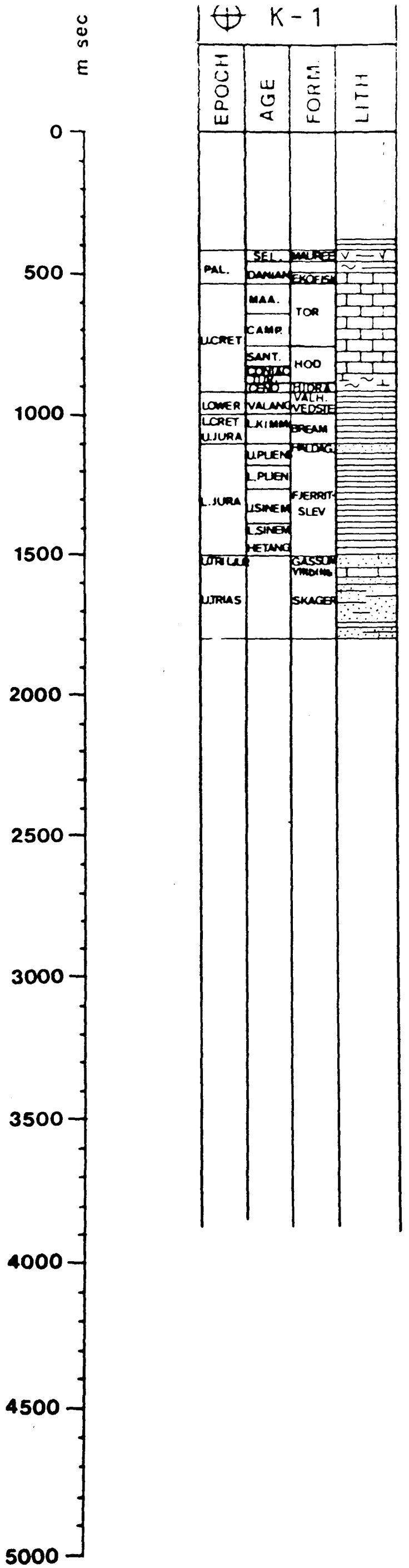

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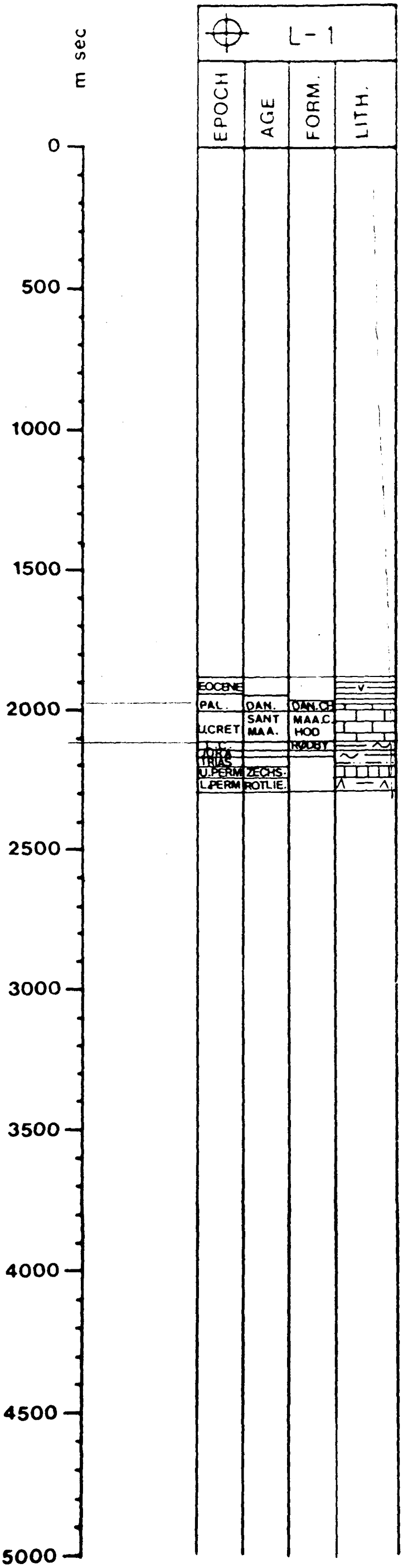

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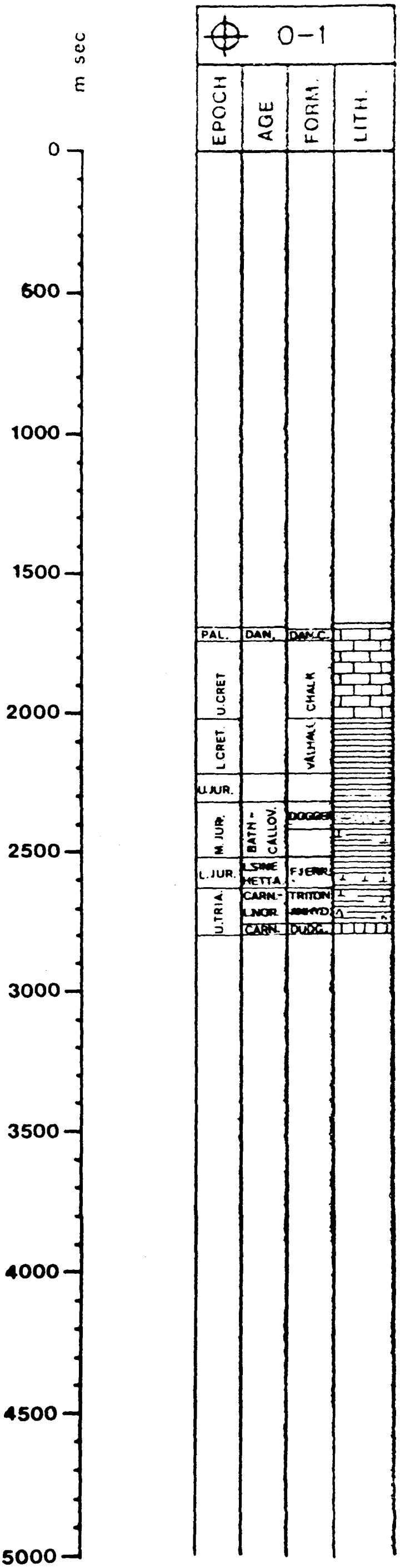

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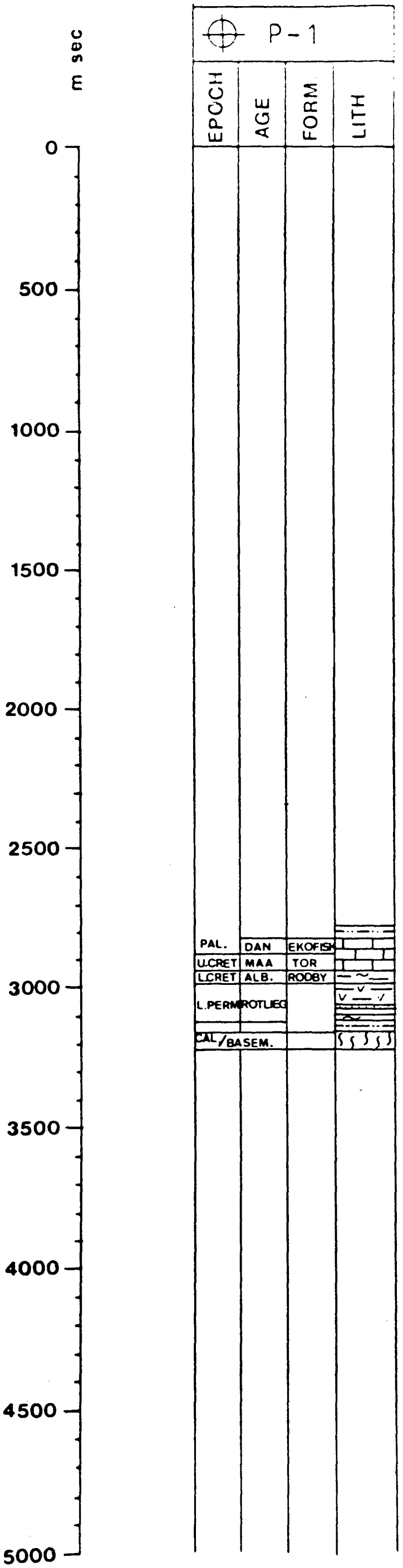

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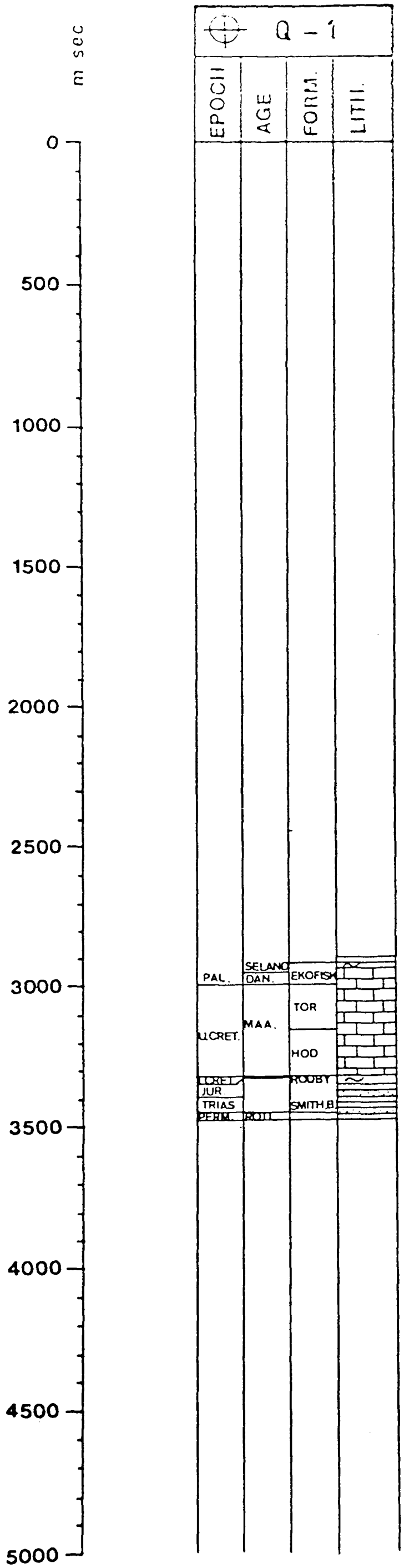

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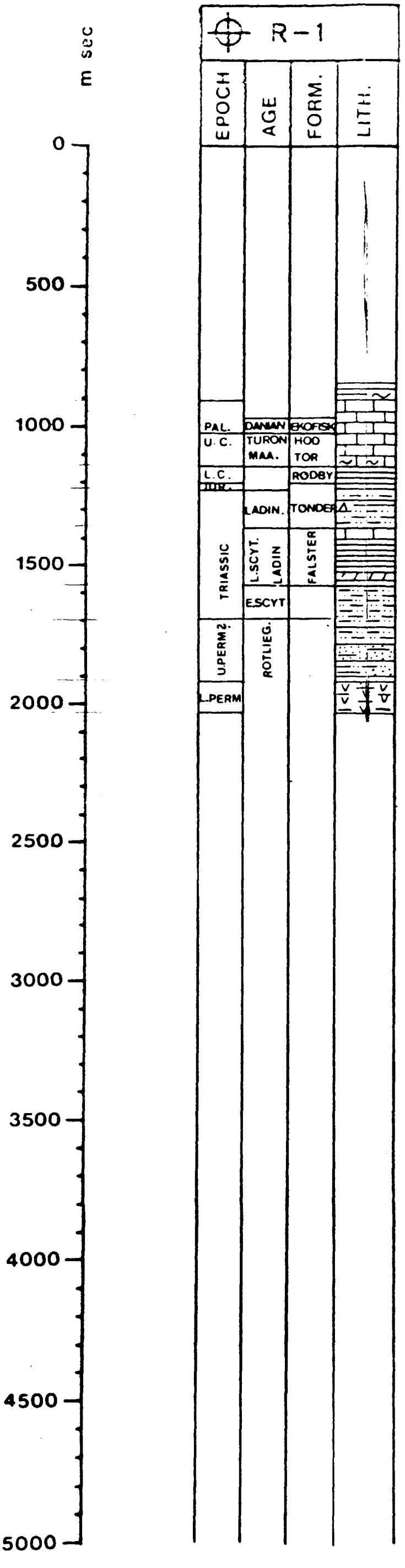

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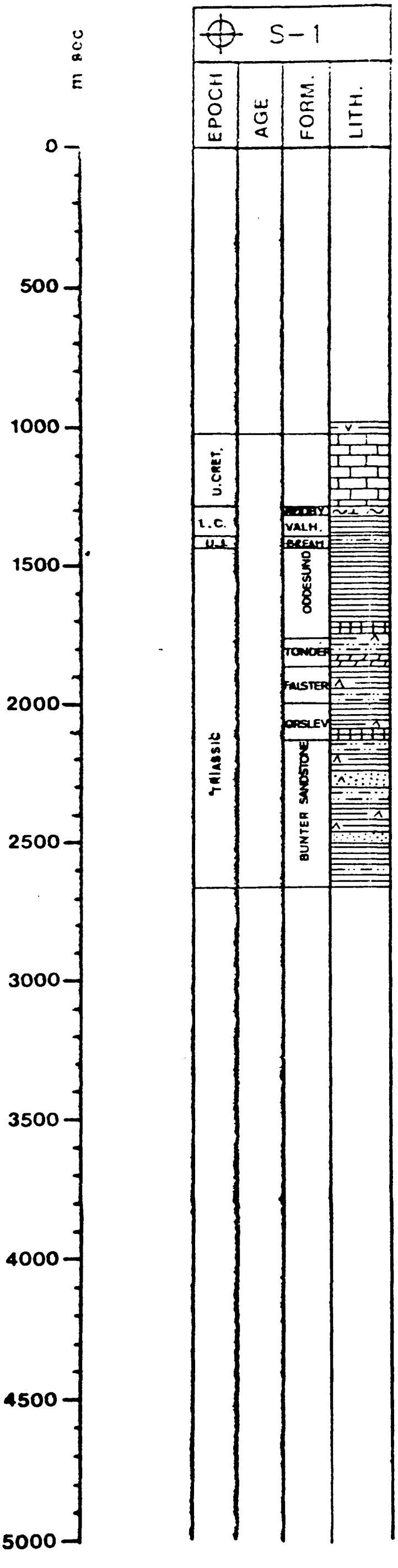

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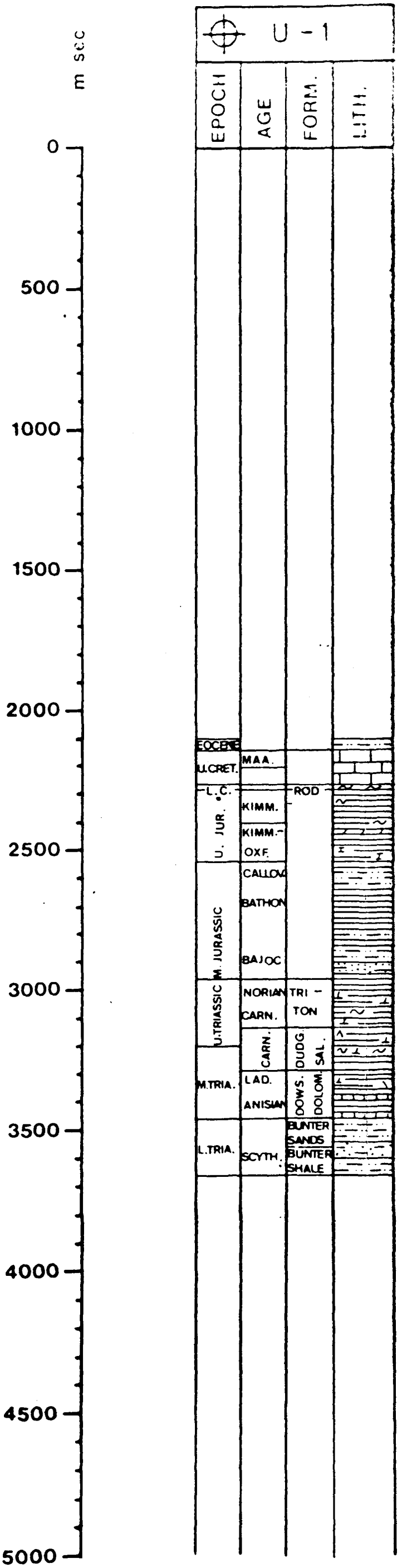

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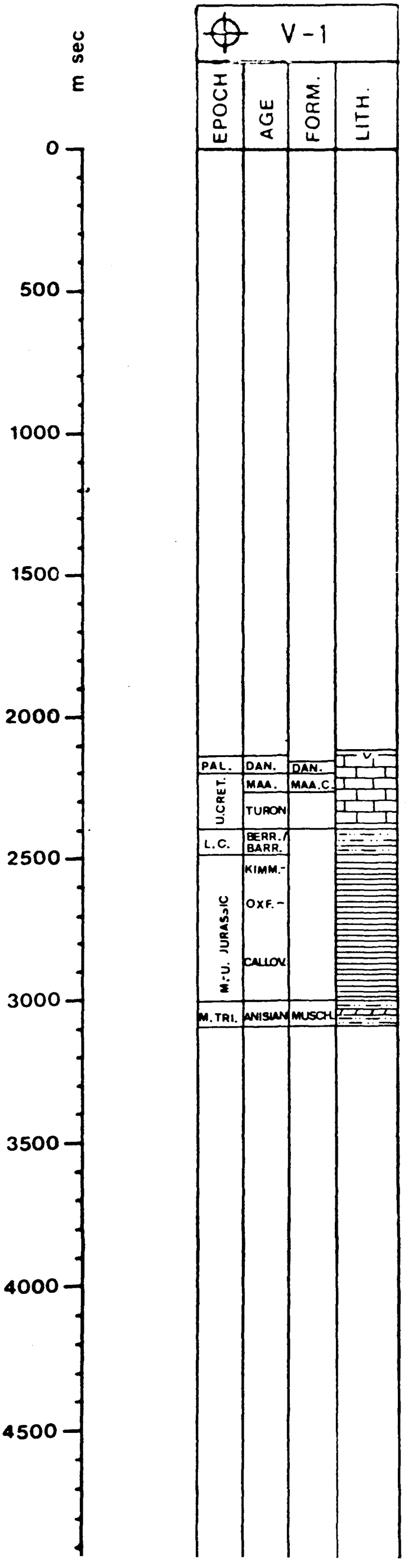

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APPENDIX B: PUBLICATIONS.

THE KINEMATICS OF INVERSION IN THE DANISH CENTRAL GRABEN.

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Submitted to Inversion Tectonics, Special Publication of the Geological Society of London, M.Cooper, and G.Williams(EDS).

ABSTRACT

The Danish Central Graben is a complex mosaic of half-grabens and structural highs that formed during Permo-Triassic and Upper Jurassic rift phases, at the confluence of the NW-SE and N-S trending elements of the Central North Sea Rift. The extensional structures forming the margins to the rift were reactivated in a reverse sense in the Late Cretaceous as part of regional inversion of basins in the southern North Sea. Deposition proceeded throughout the deformation , and thickness variation in the deep-marine Chalk succession is directly attributable to compressional deformation of the basin floor.

The total shortening across the rift amounts to only a few percent, and the structural expression of the reactivated margins is typically as low amplitude folds with minor associated reverse faulting. Compressional reactivation was restricted to basement faults, and the shallow inclination of the margin faults may have been an important factor in their subsequent reactivation. Zechstein evaporites and overpressured Jurassic shales influenced the development of some of the compressional structures.

The orientation of the growth fold axes is consistent with a net convergence in an approximately NE-SW direction. The fold axes are arranged in a segmented pattern which can be related to the underlying basement fabric. This segmentation not only resulted in variations in the amounts and style of shortening along the length of the rift, but seems to have influenced the timing of the deformation. Seismic-stratigraphic analysis of the Upper Cretaceous sequence indicates that the compressional deformation was markedly diachronous and abrupt changes in the deformational chronology are found to occur across the transverse segment boundaries.

The Danish Central Graben was inverted in Late Cretaceous times against a background of continuous deep-marine sedimentation along the axis of a former rift basin. The stratigraphy of the Upper Cretaceous Chalk in this area provides a unique record of the interplay between depositional and deformational processes in force during the inversion. Many of the other inverted rift basins of N.W.Europe were more intensely deformed, and consequently potential stratigraphic markers of the deformation either were never deposited or were subsequently exhumed and eroded.

The aim of this study was to analyse the style, distribution and timing of deformation through a combination of structural and seismic-stratigraphic interpretation of a regional grid of 5000 kms of high resolution reflection seismic data. Particular attention has been paid to the documentation of the structural geometries and evolution of early formed extensional structures. A subsidiary objective was to establish how the compressional deformation influenced Chalk depositional systems. The paper concludes by examining existing dynamic models for the regional inversion of basins in N.W. Europe in the light of observations of the deformation in the Danish Central Graben.

STRUCTURAL FRAMEWORK

In order to attempt a kinematic analysis of the Late Cretaceous inversion of the Danish Central Graben, it is important to consider the structural evolution during earlier, extensional phases of basin development. A detailed understanding of the extensional structural geometries allows us to distinguish between variations in structural style that relate to regional dynamics from those due to local variations in orientation or inclination of fault planes,or from differences in the mechanical competence of the graben fill.

The Danish Central Graben is a complex mosaic of half-grabens and structural highs that formed at the confluence of the NW-SE trending UK Central Graben and the N-S trending Dutch Central Graben. The abrupt change in orientation of the Central North Sea Rift has been attributed by Cartwright (1987), to the influence of WNW trending splays of the Tornquist Zone. The two main Mesozoic depocentres in the Danish Central Graben are the Feda Graben and the Tail End Graben (figure 1). A third, less important depocentre is the Outer Rough Basin, lying on the NE flank of the Mid North Sea High. The Tail End Graben is a NNW trending series of half-graben segments which display rotational thickening of Triassic and Jurassic sequences against the Coffee Soil Fault. The Feda Graben is, by contrast, more symmetric and is bounded on both margins by WNW trending basement normal faults. It is divided into two sub-basins by an axial fault zone, the Gert Ridge (figures 1 and 2).

Depth conversions of the 7 second two way travel time seismic data show the major bounding faults of both grabens to be planar at depth, and inclined between 30 and 40 degrees to the horizontal. The normal displacements on these faults are large, up to 8000 metres, for example, on the Coffee Soil Fault, and it seems likely that they extend for considerable distances into the crust. The structural geometry of these large basement structures is simple, and the degree of associated fracturing of the basement and sedimentary fill is minor (figures 2,3,4). Complications do however occur along the Coffee Soil Fault, at several positions along its length,where the fault plane undergoes abrupt changes of strike (figure 1). These changes of strike or offsets of the boundary fault are related to a segmentation of the Tail End Graben by WNW and NE trending transverse structural zones (Cartwright 1987).

More complex structural geometries have been interpreted from both the Olaf Fault Zone, which forms the north-eastern margin of the Outer Rough Basin, and the Jens-Otto Fault Zone, which forms the western margin to the Tail End Graben (figures 3 and 4). The complexity of the Olaf Fault Zone arises from the superposition of two en echelon normal fault suites of Upper Jurassic and Upper Palaeozoic age which dip in opposite directions. The interference of the two fault trends led to the development of complex crossing conjugate structural geometries (figures 2 and 3, also see Horsfield, 1980).

The Jens-Otto Fault Zone is a fractured monoclinal hinge which developed initially as a series of broadly NNW trending intra-basinal normal faults and subsequently acted as a fulcrum for the eastward rotation of the Tail End Graben. Stretching over the rotational hinge was alleviated by the development of crestal collapse structures. The along-strike arrangement of synthetic and antithetic faults of the crestal collapse structures of the fault zone varies with the subsidence pattern exhibited by the corresponding graben segment (Cartwright, 1987). Abrupt offsets and changes in structural style or polarity are linked to similar sense offsets or changes in the orientation of the Coffee Soil Fault by transverse fault zones of WNW and NE trend (figure 1).

EXTENSIONAL BASIN DEVELOPMENT.

Direct evidence for the timing of the onset of extensional faulting associated with the development of the North Sea Rift is lacking. Resolution of the sedimentary fill of the rift in the Danish Sector is limited to the Upper Permian and younger sequences. The Zechstein occurs throughout the Danish Central Graben, and it is probable that this area was a fault controlled trough linking the Northern and Southern

Permian Basins (Glennie,1986), suggesting in turn that rifting was established along the Tail End and Feda Grabens by the Late Permian.

The Triassic is preserved in both the Feda and Tail End Grabens but was severely attenuated by Middle and Late Jurassic erosion on the Dogger Platform-Dogger High. The sequence is sharply resolved in the Tail End Graben, and reflection configurations are observed to be parallel and continuous over large areas. This suggests that the graben floor subsided slowly and uniformly. Penetrations of Lower and Middle Jurassic sediments occur in a limited number of wells which are generally located near the apices of Upper Jurassic tilted fault blocks where erosion has incised into the earlier sequences. In the continuously subsiding graben areas, however,there is no evidence for any major phase of uplift, and there is no strongly erosional unconformity separating early and late Jurassic deposits. The Early Jurassic was a period of limited subsidence along the lines of the Triassic rift with local hiati developing in response to minor tectonic adjustments or eustatic sea level variations.

The Base Middle Jurassic is a high amplitude event on seismic that can be correlated throughout the Tail End Graben.This is a major sequence boundary separating the condensed and parallel Triassic and early Jurassic sequences from the thick Upper Jurassic sequence. The Upper Jurassic is characterised by divergent reflection configurations, which indicate a far greater rate of subsidence in this second phase of rifting. The rifting was asymmetric and controlled by rapid displacements along the Coffee Soil Fault (figures 3 and 4). Thick divergent sequences associated with the WNW trending boundary faults to the Feda Graben are also Late Jurassic in age.

Thus rotational subsidence in the Feda Graben was coeval with or closely followed that in the Tail End Graben.

Rates of subsidence varied from segment to segment in the Tail End Graben and the transverse zones were instrumental in the translation of differential rotation of the Coffee Soil Fault to the interior of the rift. The focus of the pull-apart like subsidence was in the two central segments, where as much as 5000 metres of Upper Jurassic shales accumulated in approximately twenty million years. One possible consequence of such rapid sedimentation rates of the marine shale sequences is the development of abnormal pore fluid pressures. Wells penetrating the Upper Jurassic in the Tail End Graben have encountered only a few permeable units interbedded in the shaly sequences, and there would therefore have been only limited avenues for fluid expulsion during compaction and burial. The presence of considerable volumes of undercompacted shale in the graben would have had important consequences for the later compressional phase of basin development, in that shortening of the graben fill may have been expressed in the form of tectonic compaction rather than in fault reactivation. The compaction state of the Upper Jurassic shales at the time of inversion is however unknown, and the degree to which the mechanical competence of the graben fill influenced the Late Cretaceous structural development therefore remains a matter of speculation.

The base of the Lower Cretaceous sequence is a prominent sequence boundary, which displays a srong basal onlap, but little or no erosional truncation (figures 8 and 11). This sequence boundary is often referred to as the Late Cimmerian Unconformity in the central North Sea (Rawson and Riley, 1984). It has been attributed to the onset of Lower Cretaceous rifting both in this area,(Michelsen and Andersen,1983), and over N.W. Europe (Ziegler,1982).In the Danish Central Graben, however, the widespread

onlap of truncated Upper Jurassic fault scarps by Lower Cretaceous marine shales strongly suggests that in Early Cretaceous times the basement was no longer being actively extended. Only minor fault displacements have been mapped at Lower Cretaceous structural levels, and these are more likely to have resulted from local differential compaction or Zechstein salt withdrawal than from any basement response to regional rifting. Isopach maps (Cartwright,1987; Frandsen et al.,1987) show that Lower Cretaceous depocentres are located directly above areas of maximum accumulation of Upper Jurassic shales, which is consistent with a compactional mechanism for both Lower Cretaceous subsidence and faulting. The end of the second disinct phase of rifting in the Danish Sector is therefore taken as end Jurassic.

LATE CRETACEOUS INVERSION.

The Upper Cretaceous was characterised by compressional deformation in conjunction with a phase of more regional basin subsidence. Compressional reactivation of the previously dormant rift bounding basement faults resulted in the development of reverse faults and broad, low amplitude anticlines along the rift margins.

The scale of the late Cretaceous inversion in the Danish Central Graben was minimal in comparison with basins such as the Sole Pit, or The West Netherlands Trough. The total shortening amounted to only a few percent, with maximum structural relief on inversion related structures of the order of 500 metres. This is significantly less than that observed elsewhere, and the mild effects of the compressional basin reactivation combined with the prevalence of deep marine conditions of deposition of the Upper Cretaceous Chalks ensured that the stratigraphic record of the deformation was relatively complete.

Thickness relationships in the Chalk are the product of three main factors, the regional subsidence pattern, the syn-depositional deformation of the sea floor, and the relative contributions to total sediment supply of allochthonous and autochthonous chalks. The isochore data for the Upper Cretaceous sequence presented in figure 6 shows a number of elliptical minima. These correspond to growth folds developed along the inverted basin margins. The progressive development of structural relief resulted in thinning of the Upper Cretaceous sequence from areas of maximum background subsidence towards the fold crests (figures 2,3,and 4).

STRUCTURAL STYLES OF THE INVERTED RIFT MARGINS.

Three main axes of inversion are apparent on the Base Upper Cretaceous structural contour and Upper Cretaceous isochore maps (figures 5 and 6). Compressional reactivation was localised along the SW and NE margins of the Feda Graben and the western hinge margin of the Tail End Graben (compare figure 1 with figures 5 and 6). The inversion axes are recognisable as linear arrangements of reverse faults and anticlines parallel to the underlying extensional structures. The southern segment of the Coffee Soil Fault was reactivated to a lesser extent, and reverse components of displacement are small (figure 4).

Feda Graben.

Both fault bounded margins of the Feda Graben were reactivated, and the Upper Cretaceous structural configuration displays a basin wide symmetry that reflects the earlier extensional fabric (figure 2). Growth anticlines developed on both margins. These are low-amplitude, broad asymmetric folds associated with minor thrust faults that propogated from the tips of the pre-existing normal faults during the

deposition of the Chalk. Structural relief on the folds is greatest at the Base Cretaceous sequence boundary (figures 8(a) and (b)).In both cases , the steeper limbs face away from the basin axis. Reverse components of displacement are small, and insufficient to negate the large earlier normal offsets.

Compressional reactivation was limited solely to the boundary faults, in spite of the fact that numerous large normal faults are observed to offset the graben floor along its axis. Zechstein evaporites are present at the base of the graben-fill, but do not appear to have influenced the structural development. Shortening across the graben is expressed entirely in reversal of slip and in gentle buckling of cover sequences immediately adjacent to the graben margins. Fold axes are parallel to the strike of the margins (figure 5), suggesting that motion on the fault surfaces was essentially dip-slip. Minor reverse components have been noted on faults antithetic to the bounding faults, but it is not clear whether these are riedel shears related to an oblique component of reactivation, or whether they are reverse reactivants of an extensional suite of antithetic faults (figure 8(b)).

Given the minor shortening across the Feda Graben, it seems likely that the basin margin structures were reactivated in preference to those of the axial faulted ridge by virtue of their gentler inclination. The large surface area of the basement bounding faults and the relative simplicity of their geometry would have made them highly susceptible to reactivation by horizontal compressional stresses. The sub-vertical faults of the Gert Ridge,however, would have been less favourably positioned for potential reactivation under a similar stress field.

The Tail End Graben.

The distribution of deformation associated with inversion has an asymmetry in the Tail End Graben that stands in marked contrast to the pattern described for the Feda Graben. The sense of asymmetry is opposite to that which might be expected on geometric grounds and from the preceding observations on the influence of basement structure on the geometries of the reactivated structures. The Coffee Soil Fault, which had previously controlled the subsidence of the Tail End Graben, was virtually unaffected during the reactivation. Only the southern segment of the fault shows any signs of reversal of motion. Instead the main locus of compressional deformation in the graben was on the western hinged margin (figures 3 and 4).

The structure of the western margin at Upper Cretaceous structural levels (figure 5), is a series of symmetric and asymmetric pop-up growth folds associated with reversal of motion on faults of the earlier crestal collapse structures (figures 3 and 4). Reverse offsets are less than 300 metres, but the structural relief along parts of the inversion axis is up to 500 metres, the largest of any of the compressional structures in the Danish Central Graben.

The position and orientation of fold axes along the western margin are directly related to the segmented nature of the earlier extensional structure of the graben. The style, polarity and orientation of the Triassic and Upper Jurassic components of the hinge structure change abruptly across segment boundaries and the compressional geometries generally mimic the underlying structural fabric. The sense of asymmetry in the fold axes changes polarity from segment to segment (figures 11(a) and (b)). In figure 11(a), the early collapse structure is broad, and a mini-graben developed between east-dipping and west-dipping collapse

faults. Compressional reactivation was manifested only in the propogation of the east-dipping fault as a small thrust, with associated thinning of the Upper Cretaceous sequence. In contrast, figure 11(b) shows the structure of the hinge in the adjacent graben segment to have changed to a pronounced asymmetric west verging anticline. The peculiar aspect of this structure is that the vergence of the Late Cretaceous anticline is in the opposite sense to the polarity of inclination of the 'root' extensional fault (see figure 4). The reactivation structures usually exhibit similar senses of asymmetry in both the extensional and compressional geometries (e.g figure 2). Deviation from this general observation seems, in this case, to be related to the presence of a remnant Zechstein salt pillow which straddles the deeper trace of the underlying extensional fault. The shortening appears to have gone against the grain of the 'root' fault through a partial decoupling of the Mesozoic cover on a thrust soling in the Zechstein evaporites.

Zechstein evaporites are present throughout the Tail End Graben, and it is possible that the lubricating properties of the mobile salt may have led to the focussing of the compressional reactivation onto the western margin. The strong eastward tilt of the graben floor during the Upper Jurassic rotated this potential detachment surface into an inclination ideal for reactivation under later convergence. Shortening taken up along the intra-basement transect of the Coffee Soil Fault may have been transferred to the western margin by salt lubricated displacement of the contents of the graben in preference to the more energy consuming upward propogation of the fault tip.

This essentially plane strain interpretation of the structural

evolution of the Jens-Otto Fault Zone differs from those of both Michelsen and Andersen (1983) and Vejbaek and Andersen (1987). They interpreted the inversion as the product of strike-slip deformation on the basis of the en echelon arrangement of fold axes and the development of flower structures in cross-section. There is a gross en echelon appearance to the distribution of individual fold axes along the zone, but this is related here to the extensional segmentation rather than to a late strike slip 'event'. Equally, the cross-sectional appearance does resemble that described for flower structures (Harding,1985), in that pop-up folds are bounded by downward converging fault strands which often root into a sub-vertical master fault. A flower geometry however, can also be produced by the superposition of several phases of dip-slip fault movements, particularly if there are reactivations in both extensional and compressional senses. In the case of the Jens-Otto Fault Zone, the flower-type geometry evolved in several phases, from the Triassic intra-graben step faults, through the Upper Jurassic phase of rotational hinge devlopment to the culminating compression in the Upper Cretaceous. The early formed faults were rotated into near-vertical attitudes as part of the asymmetric graben development and crestal collapse faults propogated from the antecedent faults into v-shaped structures. The final compression then buckled both the cover sequences and the crestal fault systems into their final configurations. Halokinesis and shale flowage may have contributed further to the complexities and may account for some of the rapid variation in along-strike variation in thicknesses. Due caution should be exercised,therefore,in attaching a particular kinematic significance to flower structures.

Olaf Fault Zone-Lindesnaes Ridge.

This inversion axis forms the margins of both the SW Feda Graben and the Outer Rough Basin (figure 1). The structural style is a complex, discontinuous array of reverse faults and pop-up fold axes along a broadly WNW trend (figure 5). In cross-section, the structural geometries are seen to be directly related to the underlying extensional fault systems (figures 2 and 3),with growth folds developed in response to reverse motion on the extensional faults.

The complexity of this Upper Cretaceous structure is attributed to the interference of the oppositely verging Upper Palaeozoic and Upper Jurassic basement fault suites. Detailed mapping on a grid with a 2km spacing shows that both suites are arranged en echelon and relay into new positions across a zone of intense basement fracturing in the vicinity of the P-1x well. This configuration is illustrated schematically in figure 10. The zone of mutual relay of the two fault suites is interpreted as a multiple step over zone (Aydin and Nur, 1986), which in this example is located at the intersection of the WNW controlling basement trend with a subsidiary NE trending basement lineament (figure 10). The confusing pattern of minor fold axes and fault trends seen in the Upper Cretaceous contour map (figure 5), is therefore attributed to complexities in the basement structure. Fold axes are parallel to the WNW strands of the extensional faults except in the immediate vicinity of the stepover zone where deviations in the strike of the basement grain adequately account for the Upper Cretaceous map configurations (figures 5 and 10).

The simultaneous reactivation of the two oppositely verging fault suites produced symmetric and asymmetric pop-up structures.The switch in positions of the two precursor faults across the stepover had interesting consequences for their reactivation. North-west of the stepover the folds

are inward facing towards the central basement high, but to the south-east the paired folds are outward facing as a result of the crossing over in the fault structure(figure 9). The abrupt changes in the structural style along the inversion axis can be accounted for by changes in the basement fault configuration. Parallelism of growth fold axes and the earlier structure suggests that convergence was approximately orthogonal to the basin margins in an approximately NE-SW direction.

The structural styles described from the three main axes of inversion in the Danish Central Graben are thus viewed as the products of dip-slip compressional reactivation of the pre-existing extensional basin bounding faults. The orientation of fold axes was conditioned by the basement fabric, and the detail of the structural geometries was influenced by mechanical discontinuities within the cover sequences in the form of evaporites or overpressured Jurassic shales and more importantly, by the polarity, inclination and vertical extent of the extensional faults. The segmentation of the graben along NE and WNW trending transverse lineaments during the Triassic and Upper Jurassic rift phases was equally evident in the Late Cretaceous compression, and offsets and changes in strike of fold axes followed the framework of the earlier segmentation (figure7). The segment boundaries partitioned the distribution of compressional strain into segments which are characterised by uniform orientations of fold axes. The transverse lineaments were not reactivated in a penetrative sense, but were active at depth, allowing differential degrees of shortening to be expressed from segment to segment. Their kinematic significance becomes clearer when the timing of deformation is examined in detail. The following section outlines the use of seismic-stratigraphic

methods in analysing the timing of deformation.

THE SEISMIC STRATIGRAPHY OF THE UPPER CRETACEOUS SEQUENCE.

The Upper Cretaceous Chalks of the Danish Central Graben were deposited in a slope or basin floor setting along the axis of the earlier rift in a basin that changed from subsidence confined within the rift to a regional subsidence that included the rift shoulders. Deep-marine conditions prevailed throughout the Late Cretaceous, during a period of eustatic sea level rise (Hancock,1985). Superimposed on this background, however, was the contemporaneous deformation of the depositional surface along the inversion axes. This exerted a profound influence on the patterns of sediment dispersal and accumulation. The aims of the seismic-stratigraphic interpretation were to assess the relative contributions of regional subsidence, tectonic uplift and depositional processes in the overall configuration of the Upper Cretaceous basin fill, to investigate the timing of the deformation on the inverted margins, and to consider the interactions between structural development and depositional processes.

1.Chrono-stratigraphic Interpretation.

Sequence boundaries were identified by mapping event terminations. The lower and upper boundaries of the Upper Cretaceous mega-sequence are correlatable over the entire area, but several intra-formational sequence boundaries are found to be of limited areal extent. These local unconformities are invariably found in association with inversion axes as onlap or truncation surfaces formed in response to the tectonic development of relief on the sea floor. In order to minimise the errors inherent in biostratigraphic age determinations, each local sequence boundary was correlated with as many wells as possible, and the calibrated ages

compared. Long range correlations were hampered by the common occurrence of discontinuous seismic facies. Age determinations for a single, seismically well defined event tied to a group of five wells showed a spread of the order of one stage length. This is believed to be an accurate estimate of the errors combined in seismic correlation, depth conversion and biostratigraphic determinations.

This chronostratigraphic approach contrasts markedly with that of Vejbaek and Andersen(1987). Their structural interpretation of the inversion was based on a lithostratigraphy using the subdivision of the Chalk into six units defined by electric log characteristics (Lieberkind et al.,1982). Vejbaek and Andersen (1987), stated that "local variations in the ages of the unit boundaries are here ignored in view of their uncertain datings", but go on to claim that " unit boundaries correspond to regionally correlative seismic sequence boundaries" which are considered by these authors "to represent time stratigraphic markers". Considerable diachroneity is evident, however, in the palinspastic profile presented in the original paper on the lithostratigraphy of the Chalk by Lieberkind et al.,(1982, their figure). Their unit 2, for example, ranges from Cenomanian to Campanian in age. Vejbaek and Andersen's use of the Chalk unit boundaries as markers on which to base a kinematic analysis carries with it the clear dependance on lithofacies distribution, and is viewed here as more liable to error than the chronostratigraphic approach outlined above, in spite of the range of uncertainty inherent in the biostratigraphic age determinations.

2. Timing the Deformation.

The development of growth folds along the inverted basin margins was noted previously in isochore data (figure 6) and line drawings of seismic

cross-sections (figures 8,9,11) as a gross thinning of the Upper Cretaceous sequence towards the fold axes. Closer inspection of the reflection geometries shows that this thinning is represented by onlaps and convergence onto the fold limbs. In figures 8(a) and (b) for example, thinning of the Chalk from the axial depocentre of the Feda Graben towards the margins is marked by gentle onlaps and convergence onto the inner facing limbs of the inversion anticlines. The steeper, outward facing limbs display a more pronounced onlap, particularly in the lower part of the sequence, adding an asymmetry in the stratigraphic relationships associated with the folds to that previously noted for their structure. The recognition of simultaneous onlap on both limbs of the folds towards their crests marks the earliest indication of fold growth at the surface. The sequence boundary on which the onlapping reflections truncate is thus a chronostratigraphic marker for the onset of the deformation.

In the case of the Upper Cretaceous sequence, since each reflection cycle represents the cumulative deposition over a period of several million years, it is not possible to distinguish individual episodes of relief growth beyond this degree of resolution. The growth of relief observed in the progressive rotation of the early onlap units away from the crests of the folds, (figure 8b), offers an additional means for estimating both the growth rate and the magnitude of the early structural relief.

Estimation of the ending of deformation is considerably more difficult. Extant relief may be onlapped or draped for a considerable period following the end of any fault reactivation before the effects of inversion of the basin floor are nullified. The combination of drape, onlap, and condensing in the crestal regions may give rise to considerable post-deformational thinning, and thickness variation should not,

therefore,be used as a prima facie index of active deformation (figure 8(b)).

Truncational sequence boundaries are commonly developed in the crestal areas of the inversion axes. They arise either from slope failure on the actively growing structures or from current erosion. Slump scars have been identified along the Jens-Otto Fault Zone, (figure 11b). Seismic activity was probably an important agent in triggering gravitational collapse features. The truncation surfaces are generally indicative of active deformation, but when followed by concordant units with parallel and continuous reflection characteristics as for example in figure 9, they represent erosional events which eliminated sea floor relief. As such they are markers for the end of active growth of the folds. The truncational sequence boundaries pass laterally into correlative conformities, and can be calibrated by wells sited in more fully developed Chalks of tectonically stable areas such as the Dogger Platform (figure 1).

Data on the timing of growth fold development along the main inversion axes is shown in map form in figure 12. When these data are plotted along with the outlines of the transverse lineaments described earlier, a remarkable pattern emerges. Not only are the onset and duration of the inversion highly diachronous, but the distribution of age relationships is directly related to the segmented basement structure of the rift. This suggests that in addition to partitioning the convergence in the form of segments with differing degrees of net shortening, the transverse lineaments forming the segment boundaries were also responsible for isolating temporarily stable segments from those that were being actively deformed.

3. Seismic Facies Analysis.

Numerous authors have discussed the depositional systems of the Upper Cretaceous of the central North Sea based on biostratigraphic, core and electric log data from wells (Watts et al.,1980; Kennedy,1985; Hatton,1986; Nygaard et al.,1983). This study is based on the recognition and mapping of seismic facies because it is felt that the advantages of regional mapping on a uniform and tight grid of seismic data outweigh the limitations of vertical resolution imposed by the seismic method. There is no direct equivalence between seismic facies and lithofacies. Nevertheless, the mapping of seismic facies permits the delineation of a basin wide depositional pattern beyond the spatial resolution of studies based solely on widely distributed wells.

Two seismic facies were distinguished:-

FACIES A. Parallel, sub- parallel, or wavy reflection configuration; continuous reflection character.

FACIES B.Hummocky, lenticular,mounded or occasionally progradational reflection configuration , with frequent downlap event terminations; discontinuous reflection character.

The reflection character of facies A indicates that the lithofacies are uniform over considerable areas and depositional systems were low energy. Facies A is observed in tectonically stable areas on the flanking Mid North Sea and Ringkobing-Fyn Highs and the Dogger Platform. The seismic facies is interpreted to be composed mainly of pelagic (autochthonous) chalks with admixtures of distal turbiditic chalks along the axis of the stable, subsiding graben floor (figure 13).

In contrast, the reflection configurations of facies B are indicative of higher energy depositional processes interpreted here as gravity flow deposits similar to those described by Watts et al.,(1980), Kennedy (1985), and Hatton (1986). Facies B is closely associated with tectonically active

areas adjacent to the inversion axes (figure 13). In the Norwegian sector allochthonous chalks are associated with zones of tectonic instability either along inverted fault margins or along the flanks of salt structures, and it seems likely that reworking of pelagic chalks took place in an analogous manner in the Danish sector (Nygaard et al.,1983).

Progradational configurations have been observed along the axis of the Tail End Graben (figure 13), and these are interpreted as prograding fan lobes. Slump scars and erosional surfaces are common along the crestal regions of inversion axes, and this indicates that there was substantial reworking of previously deposited chalks in areas of tectonic instability. The proximity of the locus of deposition of the products of this reworking indicates that the most common gravity flow processes were probably slumping and the formation of debris or mud flows.

Seismic facies were mapped at two stratigraphic levels, the Turonian-Coniacian and the Maastrichtian. These represent generalised patterns of deposition for 'early' and 'late' stages in the basin inversion (figure 13). Deposition of the Lower Chalk (figure 13(a)), was largely confined to the axis of the former rift, although condensed sequences of early Cretaceous age have been drilled on both the flanking highs (e.g. L-1x). Both margins of the rift were onlapped at topographic features corresponding to the underlying bounding faults (figures 8(a) and (b)). The Lower Chalk is thin to absent along the Olaf Fault Zone, the northern and southern extremities of the Jens-Otto Fault Zone, and the inverted margin of the southern segment of the Coffee Soil Fault (figure 6). Facies A is widely developed on the Dogger Platform, the Feda Graben, and the northern and southern segments of the Tail End Graben. Facies B is

confined to the central Tail End Graben, which was an area of pronounced and continuous subsidence until the Santonian. This sub-basin was delimited by topographic features controlled by the deeper structure along the margins and along the WNW trending transverse lineaments. The influence of deeper structure on the morphology of the basin floor can be seen in the onlap relationships illustrated in figure 13(a).

The Lower Chalks of facies B in the central sub-basin are considerably thicker than their age equivalents in facies A deposited on the tectonically stable platform or shelf areas. This is a reflection of both the greater subsidence rates and a greater proportion of reworked material.

The sourcing and flow paths of the allochthonous chalks were markedly influenced by the actively emerging topography along the inversion axes. Downlaps observed in Lower Chalk units indicate that the pattern of sediment dispersal was influenced by depressions in the sea floor between the inverting margin structures. In the vicinity of the V-1x well, for example, progradational reflection configurations are observed from east to west into the graben axis from the shelf area on the adjacent Ringkobing-Fyn High. The progradational units are confined to a valley-type feature occupying a saddle between two offset margin inversion structures figures 5 and 13(a)). Gravity flow chalks triggered by slope instabilities associated with the reactivation of the Coffee Soil Fault in the vicinity of the shelf edge may have been focussed into the topographic low of the central Tail End Graben through this gap in the inverting margin. It is likely that downlapping and progradational units observed parallel and adjacent to other inversion axes are also indicative of the deflective or confining role of the structurally controlled relief in the sediment dispersal patterns.

By the Late Santonian the flanking highs were incorporated in a regional phase of subsidence. As a result of the broader base of subsidence and the rise in absolute sea level, the shelf margins retreated away from their earlier, fault controlled positions on the rift margins, and the most easily mobilised source of allochthonous chalk material was thus removed far from the potential repository on the basin plain. Nevertheless, facies B is widely recognised in Upper Chalks and is closely associated with inversion axes (figure 13b). By Campanian and Maastrichtian times, the main locus of compressional reactivation had shifted towards the central area, along parts of the Olaf and Jens-Otto Fault Zones. Sea floor relief amounted to over 100 metres along these growth folds, and there is considerable evidence of redeposition from the crestal regions to immediately adjacent areas. The supply of allochthonous material was almost entirely local, but fine grained distal turbiditic chalks may have reached areas of the basin floor that were remote with respect to active inversion axes.

The distribution of the two seismic facies thus shifted progressively in accordance with changing patterns of regional subsidence and inversion. The dominantly pelagic chalks of facies A are widely distributed in more tectonically stable areas, whilst the allochthonous chalks display patterns of sourcing, dispersal and accumulation that were strongly influenced by structurally induced topographic features corresponding to axes of inversion. A picture emerges of the control exerted on the depositional systems of the Upper Cretaceous by both the dormant and the reactivated elements of the structural framework. The relationship between active tectonics and depositional processes is significant in view of the importance that predicting the distribution of allochthonous chalks has in

exploration for high permeability chalk reservoirs. The organisation of the depositional systems re-emphasises the significance of diachroneity in timing the compressional deformation and in the stratigraphic and structural development of this region in the Late Cretaceous. of the Late Cretaceous.

DISCUSSION.

The most significant result of this analysis of Late Cretaceous inversion in the Danish Central Graben is the recognition of a diachronous pattern in reactivation of the former rift margins that was closely connected to a network of transverse lineaments. Analysis of the kinematic data (fold axis orientations, motion and timing of reactivated faults) along the inversion axes, indicates convergence in an approximately NE-SW direction between the rigid, undeformed rift flanks. Strain was partitioned longitudinally along the rift by transverse lineaments aligned roughly parallel to the transport direction acting in a tear sense. The question that remains is how such a system of transverse segmentation and diachronous switching of deformation relates to the regional inversion activity.

Inversion of the Mesozoic basins of N.W. Europe has been attributed by Ziegler (1982) to the long range transmission of compressional stresses generated at the Alpine convergent margin. Previous analyses of inversion in the Danish Central Graben have concurred with this causative mechanism, and describe the structural evolution in terms of strike slip or transpressional deformation resulting from Alpine collisional tectonics (Michelsen and Andersen,1983; Vejbaek and Andersen,1987). Ziegler (1982) likens the behaviour of the previously thinned Mesozoic basins to shear pins collapsing under tangential stresses. He rightly emphasises the importance of pre-existing crustal discontinuities in the overall pattern of intra-plate compressional deformation, but presents no basis for the transmission of the stress fields postulated for the deformation. His dynamic model is derived in part from his observations that inversion movements were "more or less synchronous" in widely separated basins, and that "Sub-Hercynian and Laramide compressional and wrench deformations of

the Alpine foreland coincide with major orogenic events in the Alpine domain."

Support for Ziegler's hypothesis for basin inversion in N.W. Europe has come recently from micro-structurally based reconstructions of Tertiary stress patterns in the Alpine foreland (Letouzey,1987; Bergerat,1987). These studies suggest that the stress patterns in the near-surface were oriented uniformly over large areas of the foreland. These authors relate the evolution of the regional stress fields to the relative motion vector between the African and European Plates. Opinions differ, however, as to the relative motion vectors (compare Savostin et al.,1986, Livermore and Smith,1985, Helman, in prep). Moreover, the crucial period from the point of view of basin inversions in the North Sea is the Late Cretaceous. This time period is largely unconstrained in kinematic recontructions because it coincides with the Cretaceous Magnetic Quiet Zone.

There is as yet no general agreement on the specific timing of 'orogenic events' along the Alpine system (Dewey et al.,1973; Smith and Woodcock,1982), nor indeed is there a consensus on what exactly constitutes an orogenic 'event', and still less how this might be correlated with hypothetical stress fields. As a result of the uncertainties in the plate kinematics and the detailed timing of collisional events, hypotheses that relate basin inversion in N.W. Europe to Alpine collisional orogenesis through the transmission of stress across an highly anisotropic continental interior cannot be tested in any straightforward way.

Ziegler (1982) suggested that compressional stresses in the foreland in the Late Cretaceous " had an essentially N-S orientation". In the Danish sector, Michelsen and Andersen (1983) were impressed with the apparent en echelon arrangement of fold axes, and concluded from this observation that inversion was "caused by a compressional or strike-slip stress regime",

yet they gave no indication of the orientation. Vejbaek and Andersen(1987) refer to a likely stress system for the Late Cretaceous as " governed by N-S to NNW-SSE directed right lateral strike slip motions" but their dynamic interpretation of fault kinematics shows a NE-SW orientation for the principal compressive stress (their figure 17).

Interpretations of possible stress field orientations in areas such as the Danish Central Graben are hampered by the strong influence that pre-existing lines of mechanical weakness exert on the distribution of deformation. Nevertheless, the ubiquitous development of NW-SE oriented fold axes argues strongly for compression in a NE-SW direction irrespective of whether the compression was the product of horizontal deviatoric stress or of convergent motion of the bounding regions. It is possible that local refraction of a regional N-S stress field across the WNW and NE trending crustal discontinuities could account for the NW-SE preferred orientation particularly if allowance is made for the orientation of the early extensional structures. However, it is more difficult to envisage how N-S oriented compressive stress fields could be refracted in such a way as to account for the longitudinal diachroneity in the deformational response. It seems highly unlikely that a regional force field could be focussed simultaneously into the two outer segments of the basin whilst leaving the central segment in some form of shadow zone (figure 12).

In addition to the problems arising from mechanical anisotropy of the early extensional structures, there are sub-horizontal mechanical discontinuities at various levels in the crust and lithospheric mantle which should also be considered. It is not clear how stress trajectories would be affected at these boundaries and how individual structures would react. Stress transmission might reasonably be predicted to be more effectively achieved in crystalline basement than in semi-consolidated

cover rocks. Predictions of the likely reactivation of structures made on this basis are at variance with observations presented in this paper. The Coffee Soil Fault has the largest basement surface area of any of the faults in the Danish Central Graben, and might, therefore have been the most vulnerable to reactivation by horizontal compressive stress, yet it was inverted to only a limited extent.

The European craton is a mosaic of Precambrian, Caledonian and Variscan massifs bounded by linear fault zones of great antiquity and complexity that show evidence of repeated reactivation. An outline map of these persistently active faults is presented in figure 14. The mosaic is dominated by several fundamental lineaments(megashears), which are oriented NW-SE. The megashears dissect the ancient massifs. Mesozoic rift basins seem to have formed at offsets or relays of subsidiary splays of the main fault trends. The Pays de Bray Megashear for example, passes at its north-western termination into two splay basins along the Malvern Line and along former Variscan fractures in the Bristol Channel. In the Danish sector, WNW trending splays of the Tornquist Zone intersect the North Sea Rift and controlled the positioning of the rift-rift type offset along the NW-SE trending Central Graben (Cartwright,1987). The transverse lineaments recognised on a small scale in the Danish Central Graben, and which appear to have dictated the kinematic response to extension and compression thus link into the broader framework of N.W. European continental lineaments.

N.W. Europe has a rhombohedral shape, bounded on its NE and SW faces by two of the largest megashears, the Tornquist Zone and the Armorican Shear Zone (figure 14). The NW and SE faces of the rhomb are represented by the divergent and convergent margins of the N. Atlantic Ocean and the Alpine-Carpathian collisional zone respectively.The rhomb is bisected by a

striking alignment of NW trending faults that continue in a linear corridor from the SW border zone of the Bohemian Massif, along the NE margin of the London-Brabant Massif and on into the Pennine Massif possibly as the Craven Fault system. It may extend further, towards a pronounced offset in the western U.K passive margin along a N.W trending series of crudely en echelon Mesozoic graben in the Irish Sea-Solway Firth area. Several authors have drawn attention to the possibility that the Early Tertiary magmatic centres of the Hebridean Province were preferentially located above the trace of deep seated N.W. trending lineaments (e.g Watson,1985). Hall (1986) has recently identified the Cruachan Lineament in the Western Highlands from structural, aeromagnetic and gravity data and has related it to the intrusive centres on Skye and Mull. Pegrum (1984) has proposed that the Tornquist Zone may continue into the oceanic lithosphere west of the Orkneys as the Wyville-Thomson Ridge, a major offset transform zone in the N. Atlantic. It is suggested here that the abrupt offset of spreading axes and margin trends at the northern end of the Rockall Trough (figure 14),may have been controlled by a system of continental megashears in an analagous fashion to that described for the Tornquist Zone. This corridor-type alignment of major fractures running from Bohemia to the Atlantic margin is here termed the Trans-European Lineament(figure 14). The rifted basins of the plate interior are thus connected to the faces of the rhomb by the network of megashears.

It is likely that plate boundary forces exerted on the faces of the rhomb are relayed to the interior by translation of displacement along megashears. A pattern of intra-plate deformation based on a network of large-order strike-slip faults was proposed by Arthaud and Matte (1977) to account for pull-apart basin formation in Western Europe in the Late Carboniferous. This mode of intra-plate deformation seems equally

applicable to the later compressional reactivation of many of those Late Carboniferous basins.

Differential displacement imparted to the faces of the rhomb through variations in convergence rate or mode along strike, or through spreading centre jumps or spreading rate variations across the lineament-linked transforms, might be communicated by jostling of the rigid massifs along the bounding megashears. Both the massifs and the intervening 'shear-pin' basins might be subjected to convergence, reactivation and uplift not as a result of regional stress transmission, but as a result of displacement transfer along the vertical crustal or lithospheric lineaments. This would seem to offer a more efficient means of communication between the plate boundary and its interior than transfer of displacement on horizontal detachments.

When the Late Cretaceous and Tertiary inversions are considered in the regional framework an interesting pattern in the distribution of compressional deformation is observed. Basins in the NE half of the rhomb experienced their main phase of inversion during the Late Cretaceous, whilst those to the SW of the Trans-European Megashear, were inverted in the Early-Midddle Tertiary (figures 15 and 16). This distribution is a reflection of the interactions on all four faces of the rhomb and not,as Ziegler (1982) has suggested, the product of collisional events on the SE margin alone.

As mentioned earlier there is considerable uncertainty in the kinematics at the four boundaries, but the schematic reconstructions shown in figures 15 and 16 are included to suggest how the megashears may have acted to partition the displacements introduced at the plate margins. Net convergence for example in Eocene-Oligocene times was taken up in the inversion of the Western Approaches, Channel, Wessex, Celtic Sea and Manx

Basins, and uplift of the Irish, Welsh and Scottish Massifs. The SW half of the rhomb may have been subjected to a vice-like convergence as a result of the NE-ward propogation of the newly spreading N. Atlantic and the collisional interactions in the Pyrenees and western Alps.

The role of crustal and lithospheric heterogeneities in distributing deformation resulting from plate boundary interactions is becoming more generally recognised (Sutton and Watson,1986; Daly,1986; England and Houseman,1986). It is not yet clear whether intra-plate deformation is related to plate margin processes through the generation and transmission of stress fields which then reactivate pre-existing structures, or whether the deformation is stimulated by the transfer of displacement into the interiors along vertical lineaments. In either case, observations of the timing and distribution of intra-plate deformation described here for basin inversion in N.W. Europe emphasises the importance of fundamental continental lineaments at all scales of structural evolution.

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FIGURE CAPTIONS.

Figure 1. Generalised tectonic elements map of the Danish Central Graben.

Figure 2. Schematic cross-section of the Feda Graben. Upper Cretaceous sequence amplified to clarify thickness variations across inverted basin margins. Note the relative simplicity of the planar basement faults. B.Z.,Base Zechstein; B.Ju.,Base Upper Jurassic; B.V.,Base Volgian; B.Kl., Base Lower Cretaceous; B.Ku., Base Upper Cretaceous; B.T., Base Tertiary.

Figure 3. Schematic cross-section,Outer Rough Basin - Central Tail End Graben. Contrast inversion geometries with Fig.2. No reactivation of Coffee Soil Fault- Lower Cretaceous and Lower Chalk onlap the fault scarp.

Figure 4. Schematic cross-section, Central- Southern Tail End Graben. Note possible influence of mobile Zechstein evaporites in reversed polarity of shallow inversion structure on western margin relative to deeper structure.

Figure 5. Base Cretaceous structural contour map. Main inversion axes located along graben margins are characterised by discotinuous arrays of reverse faults and ellipsoidal anticlines.

Figure 6. Upper Cretaceous isochore map (thickness in time measured normal to bedding). Syn-depositional fold axes are marked by pronounced contour minima and maxima, often seen to offset abruptly or change strike at zones of transverse contour lineations.

Figure 7. Transverse lineaments and inversion axes. Upper Cretaceous growth folds form a segmented pattern related to the deeper structural fabric. Within each segment, the axes are aligned uniformly, but change strike or are offset along linear traces recognisable in fig.6 and which correspond to transverse fault

zones in the basement.

Figure 8. Line drawings of seismic data across the inverted margins of the Feda Graben. Asymmetric growth folds are developed on both margins as a result of a dominantly dip-slip reversal of motion on the bounding basement normal faults. Note the thinning of the Chalk through a combination of onlap and convergence.

Figure 9. Line drawing across the Olaf Fault Zone showing a complex interference pattern between Upper Palaeozoic and Upper Jurassic basement normal faults. The later inversion structure owes its complexity in three dimensions to this interference.

Figure 10. Schematic representation of the structural evolution of the Olaf Fault Zone. Two phases of extensional faulting along relaying en echelon suites followed by compressional reactvation. The relaying at the stepover zone may have nucleated at the intersection with a transverse zone in the basement.

Figure 11. Line drawings across two neighbouring segments of the Jens-Otto Fault Zone. Note the contrast in geometries of both the extensional and compressional structures.

Figure 12. Kinematic data. Normals to inversion fold axes are oriented between N.20 E. and N. 80 E., suggesting that convergence of the bounding highs was in an approximately NE-SW direction. The onset and duration of deformation shown on the figure for the major inversion axes was determined using seismic-stratigraphic techniques. The compressional deformation was markedly diachronous, and the boundaries between segments with different deformation histories correspond to the transverse lineaments of fig.7. This indicates that the transverse lineaments were instrumental in partitioning the shortening along the length of

the rift, and controlled the longitudinal migration of the main loci of the compressional reactivation.

Figure 13. Seismic facies maps of representative sequences of Lower and Upper Chalks.

Figure 14. Fundamental fault lineaments, basins and massifs in Western Europe. The data is abstracted mainly from Ziegler(1982), with additional interpretations from Cartwright(1987), and Pegrum (1984). The Trans-European Megashear is interpreted as a strong NW trending alignment of long-lived crustal scale faults, often having appreciable strike-slip components, that constitutes a corridor of deformation perhaps comparable in magnitude to the Tornquist Zone.

Figure 15. Possible boundary conditions on the western European 'rhomb', and the relationship between the distribution of basin inversions and uplifts of micro-cratonic massifs and the transfer of displacement along intra-plate discontinuities. The Trans-European Megashear separates a NE half of the rhomb, where inversions and uplifts are mainly of Late Cretaceous age, from a SW half, where the inversions and uplifts are of Early Tertiary age. This large scale provinciality in the timing of basin inversion suggests that net convergent displacements on the faces of the rhomb may have been relayed for large distances into the plate interior along a connected network of crustal or lithospheric fractures.

Figure 16. Merlin Geophysical seismic line across the Central Tail End Graben, illustrating the general features of inversion of the margins during the Late Cretaceous, followed by a broad axio-symmetric up-bulge of the graben during the Early Tertiary.

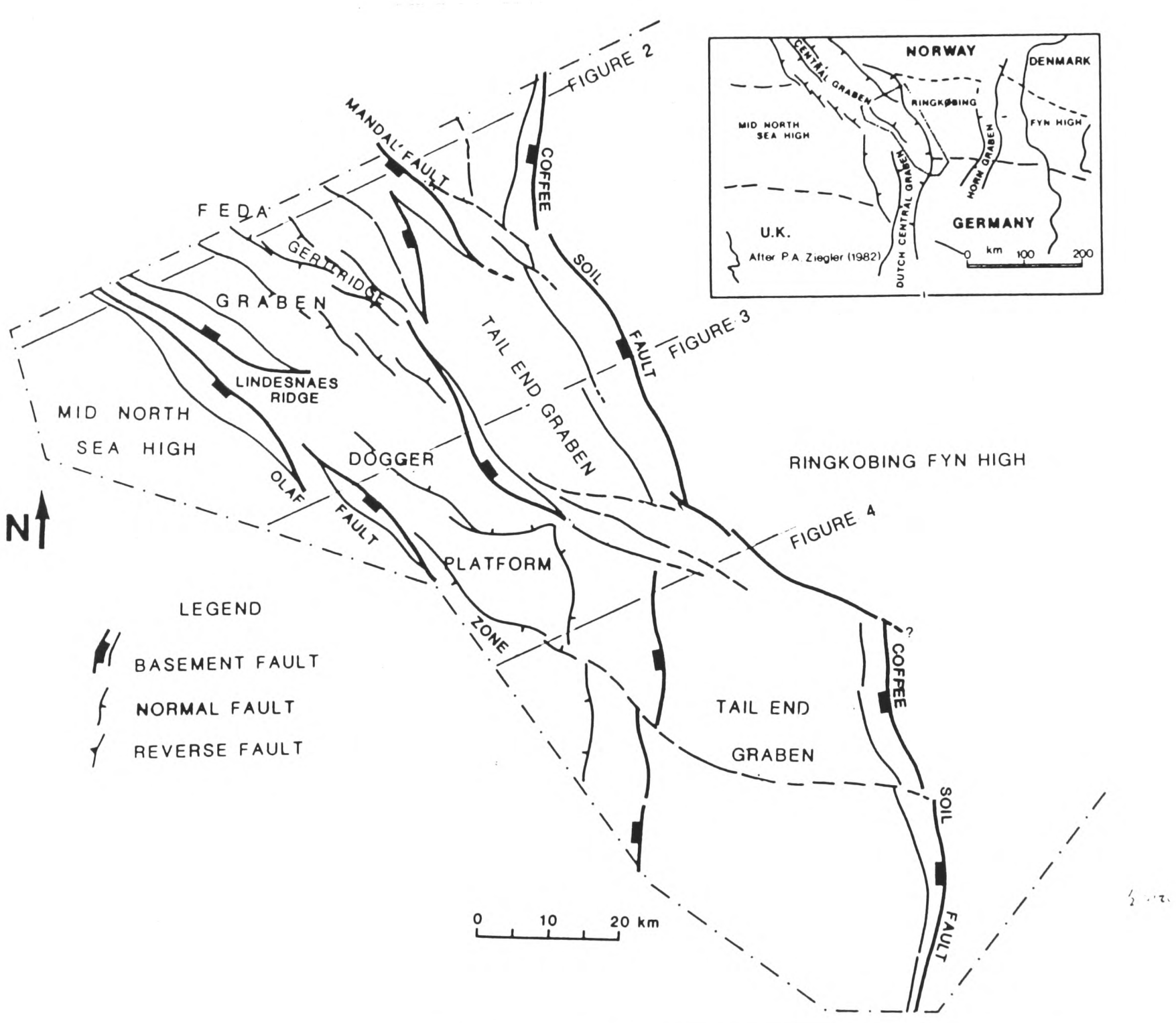

NORWAY
DENMARK
CENTRAL GRABEN
RINGKØBING
MID NORTH SEA HIGH
FYN HIGH
HORN GRABEN
DUTCH CENTRAL GRABEN
GERMANY
U.K.
After P.A. Ziegler (1982)
0 km 100 200
FIGURE 2
MANDAL FAULT
COFFEE
FEDA
GERTRUDE
GRABEN
SOIL
FAULT
FIGURE 3
LINDESNAES RIDGE
TAIL END GRABEN
MID NORTH SEA HIGH
DOGGER
RINGKOBING FYN HIGH
OLAF
FAULT
FIGURE 4
N
PLATFORM
LEGEND
ZONE
BASEMENT FAULT
NORMAL FAULT
REVERSE FAULT
TAIL END
GRABEN
COFFEE
SOIL
FAULT
0 10 20 km

FIGURE 1

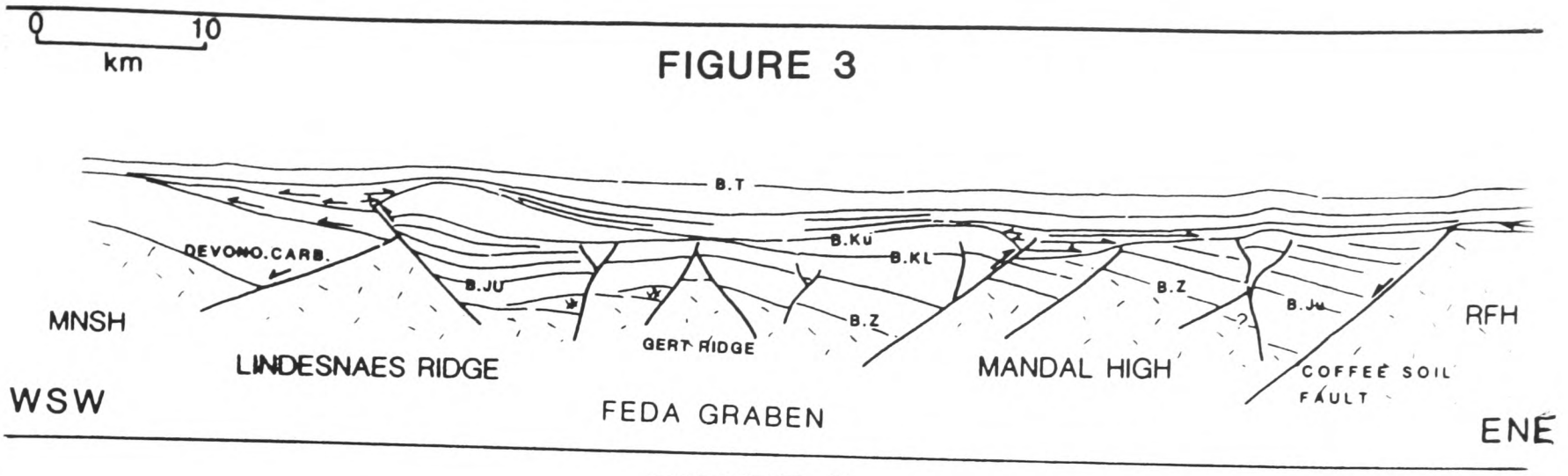


FIGURE 3

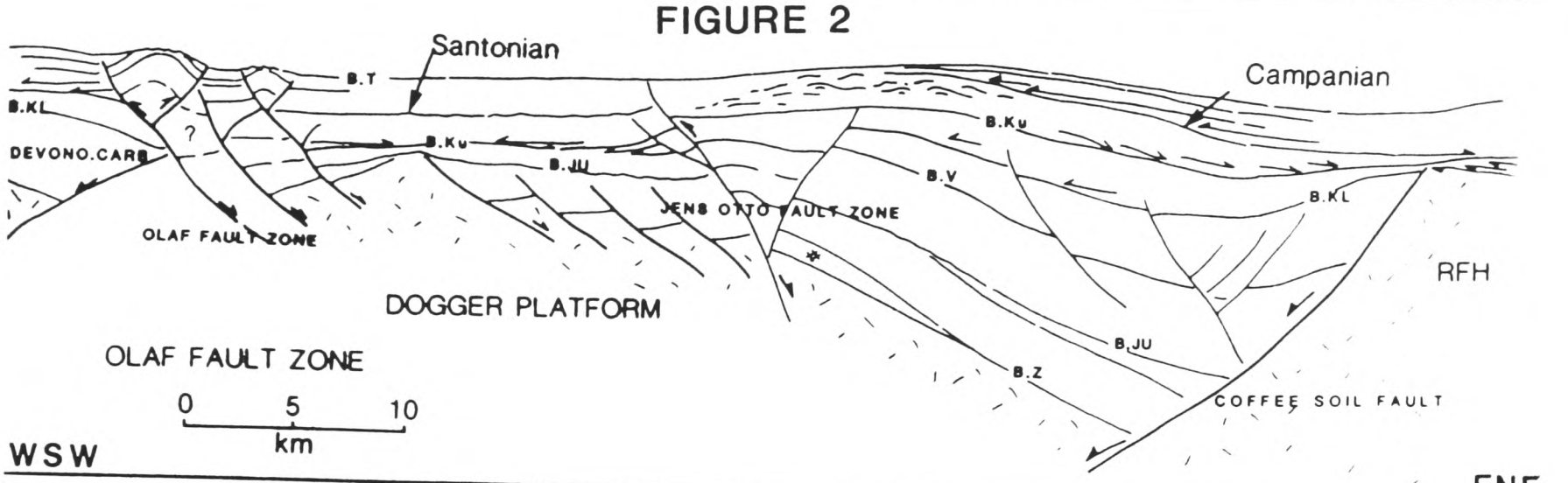


FIGURE 2

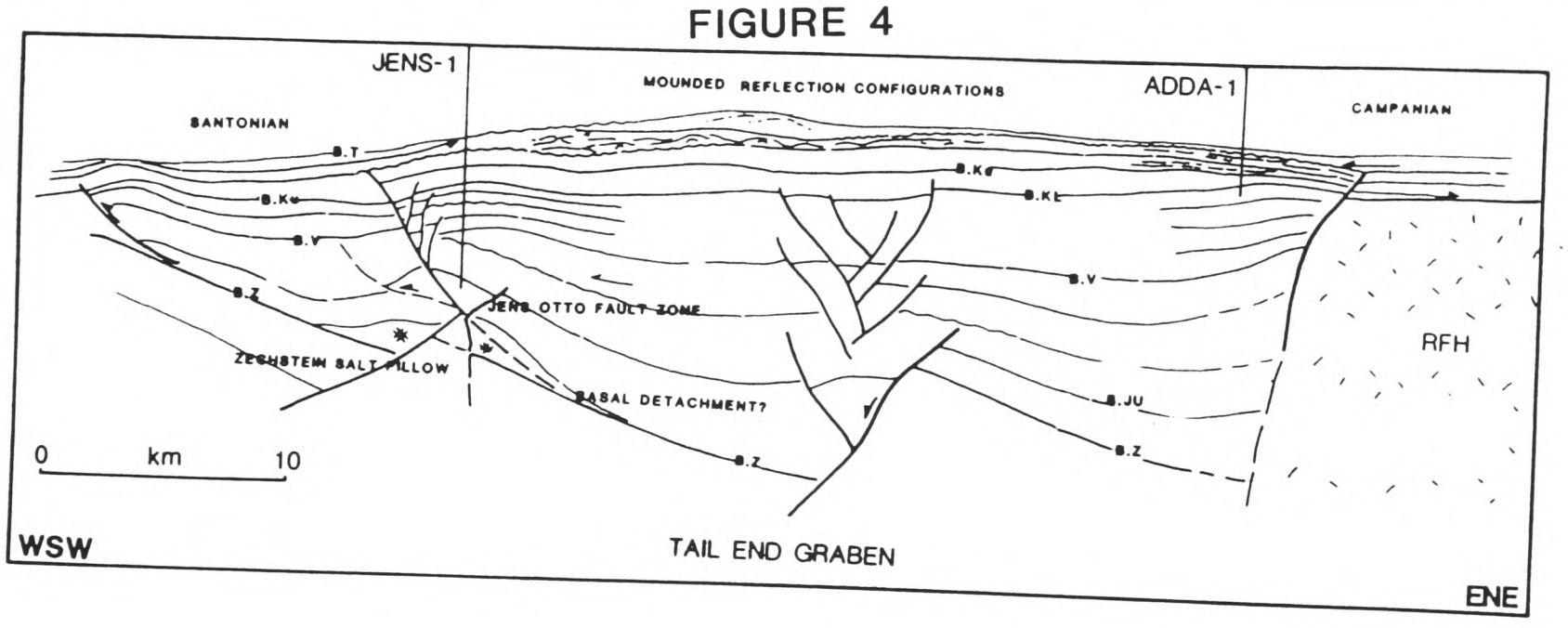


FIGURE 4

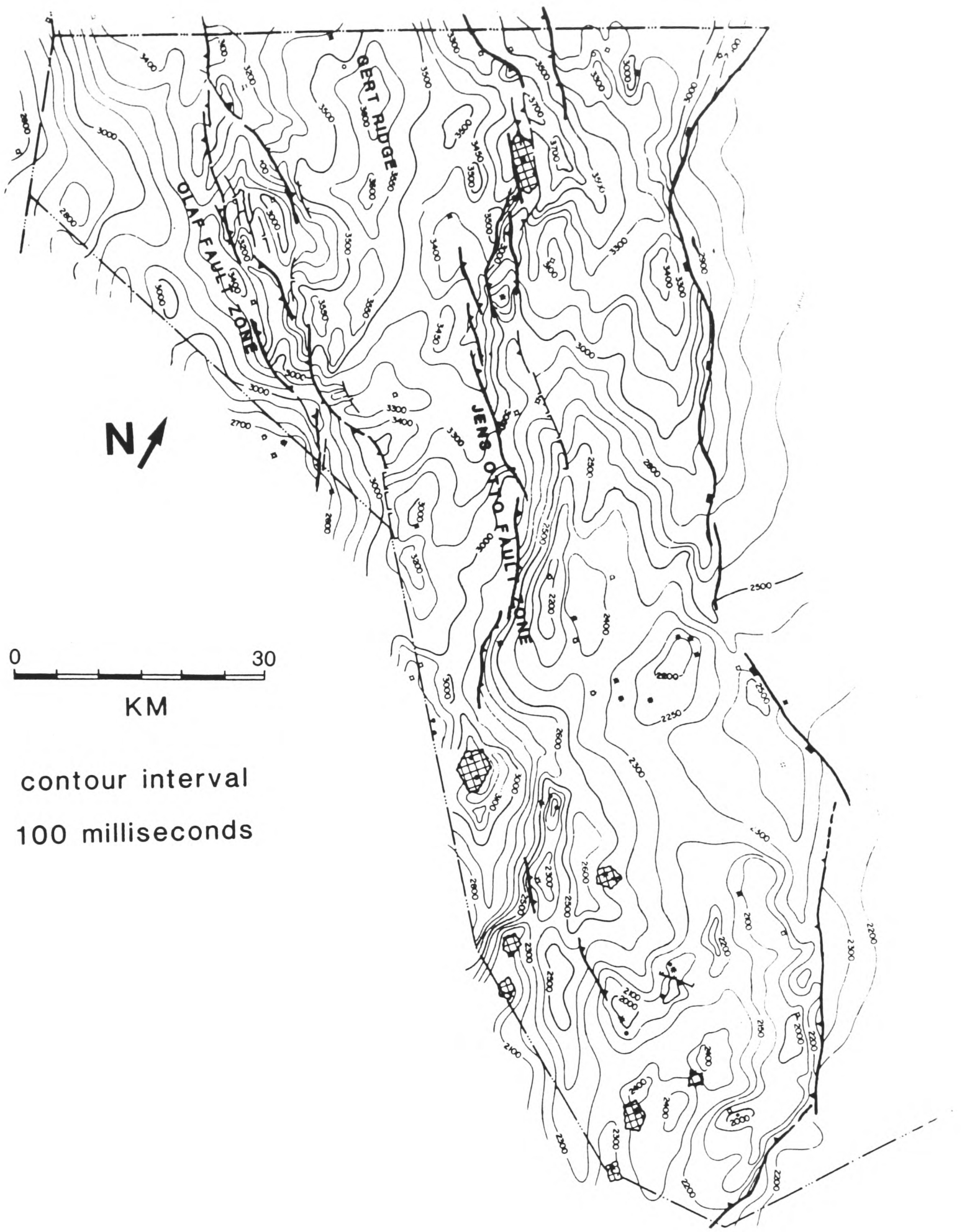

GERT RIDGE
OLAF FAULT ZONE
JENS OLSEN FAULT ZONE
N
0
30
KM
contour interval
100 milliseconds

FIGURE 5

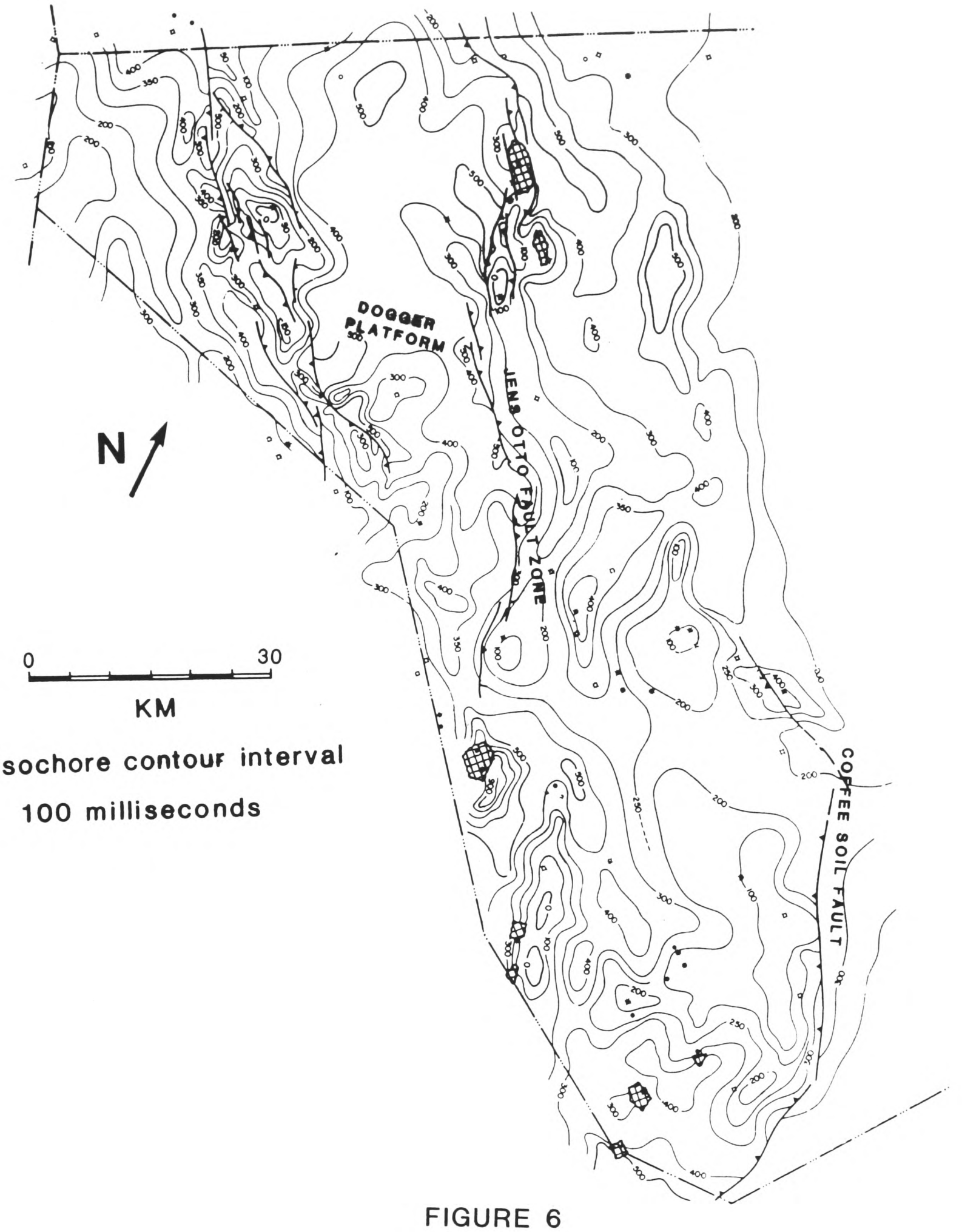

DOGGER PLATFORM
JENS OTTO FAULT ZONE
COFFEE SOIL FAULT
N
0
30
KM
isochore contour interval
100 milliseconds

FIGURE 6

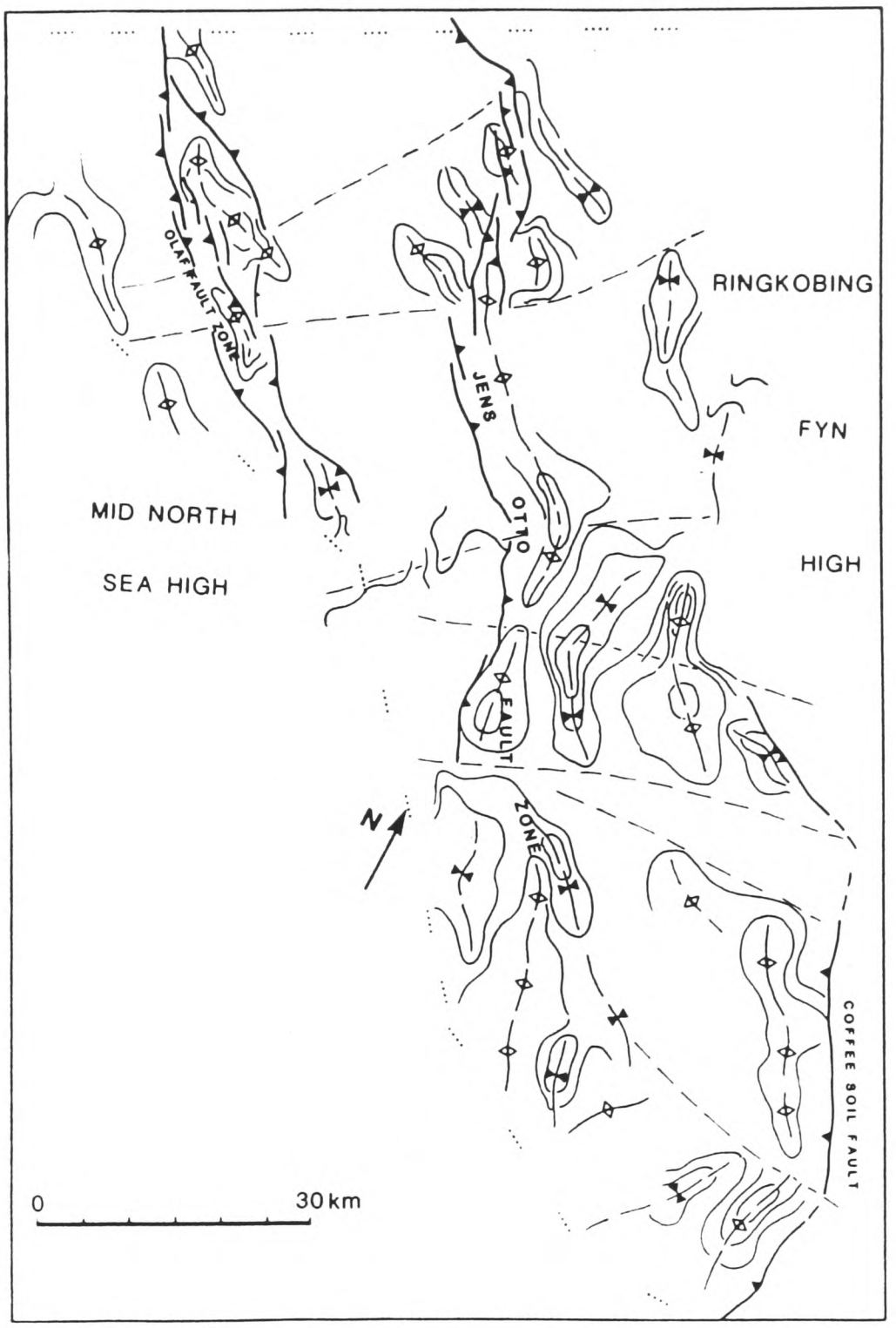

OLAF FAULT ZONE
JENS
OTTO
RINGKOBING
FYN
HIGH
MID NORTH
SEA HIGH
FAULT
ZONE
N
COFFEE SOIL FAULT
0
30 km

FIGURE 7

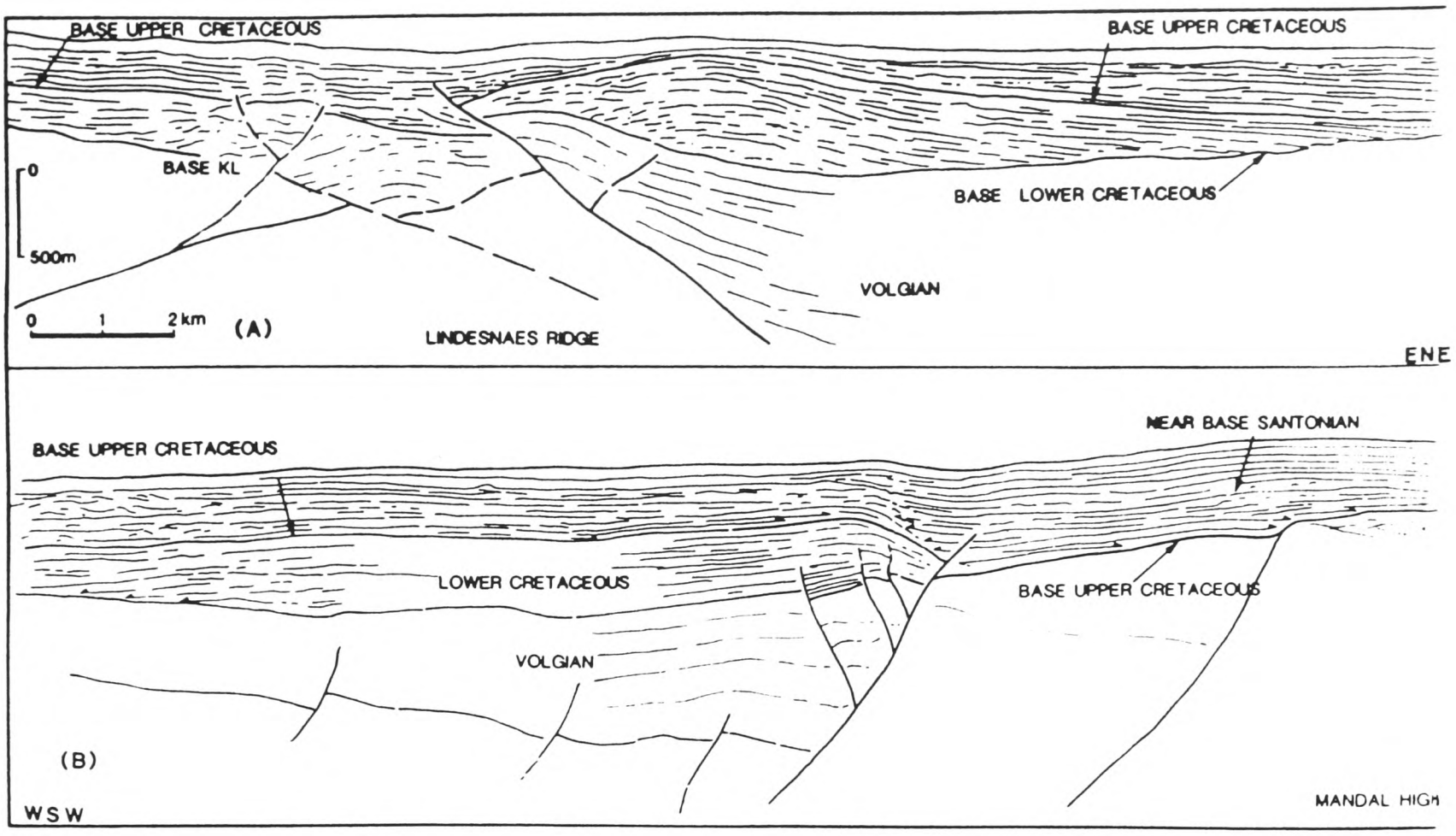

BASE UPPER CRETACEOUS
BASE UPPER CRETACEOUS
BASE KL
0
500m
BASE LOWER CRETACEOUS
VOLGIAN
0 1 2 km
(A)
LINDESNAES RIDGE
ENE
NEAR BASE SANTONIAN
BASE UPPER CRETACEOUS
LOWER CRETACEOUS
BASE UPPER CRETACEOUS
VOLGIAN
(B)
WSW
MANDAL HIGH

FIGURE 8

FIGURE 9

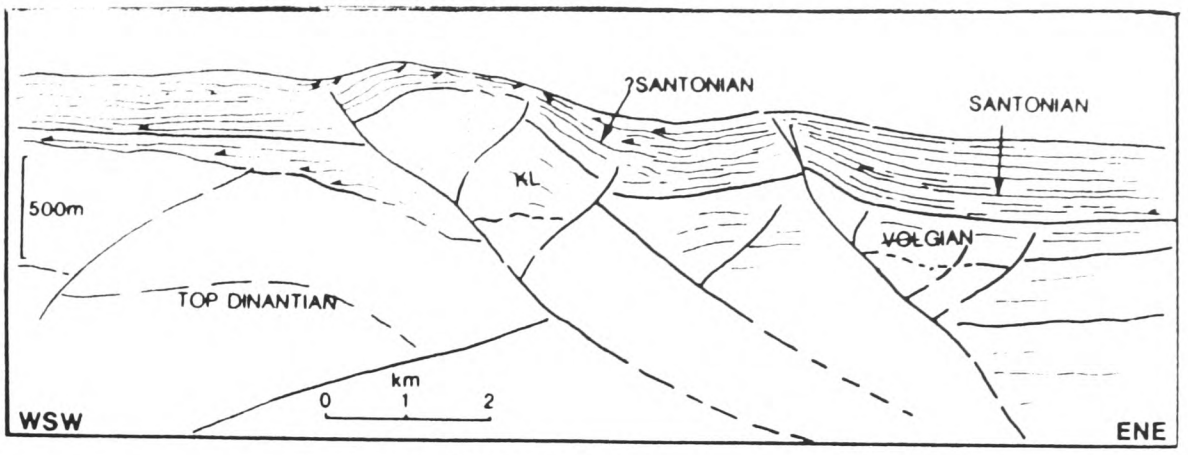
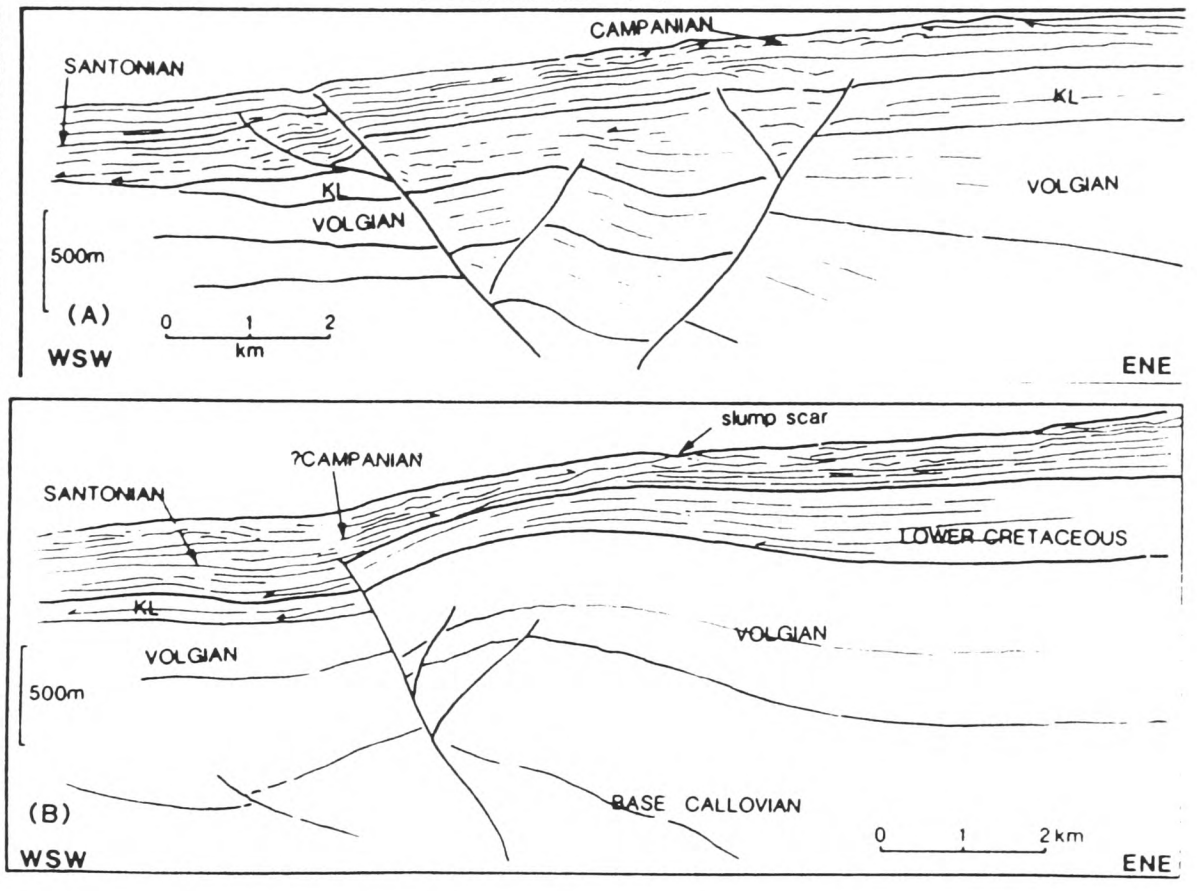


FIGURE 11



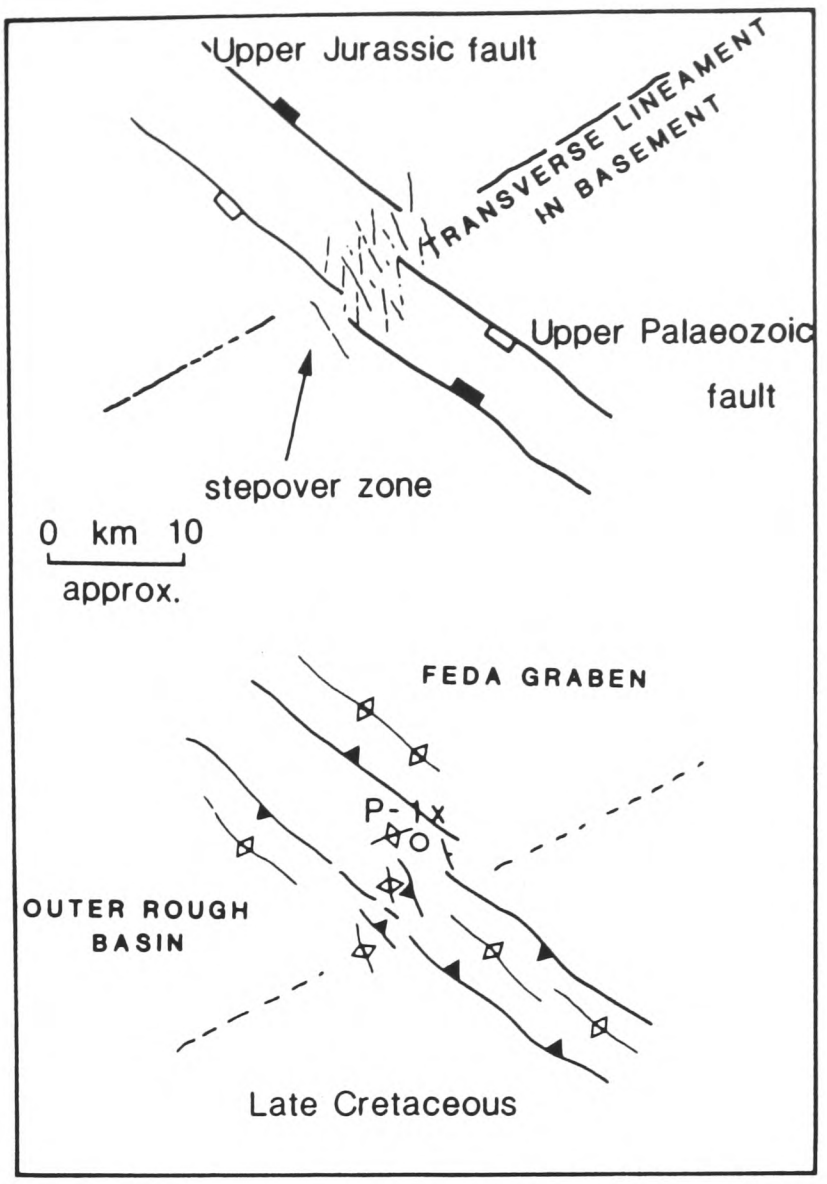


FIGURE 10

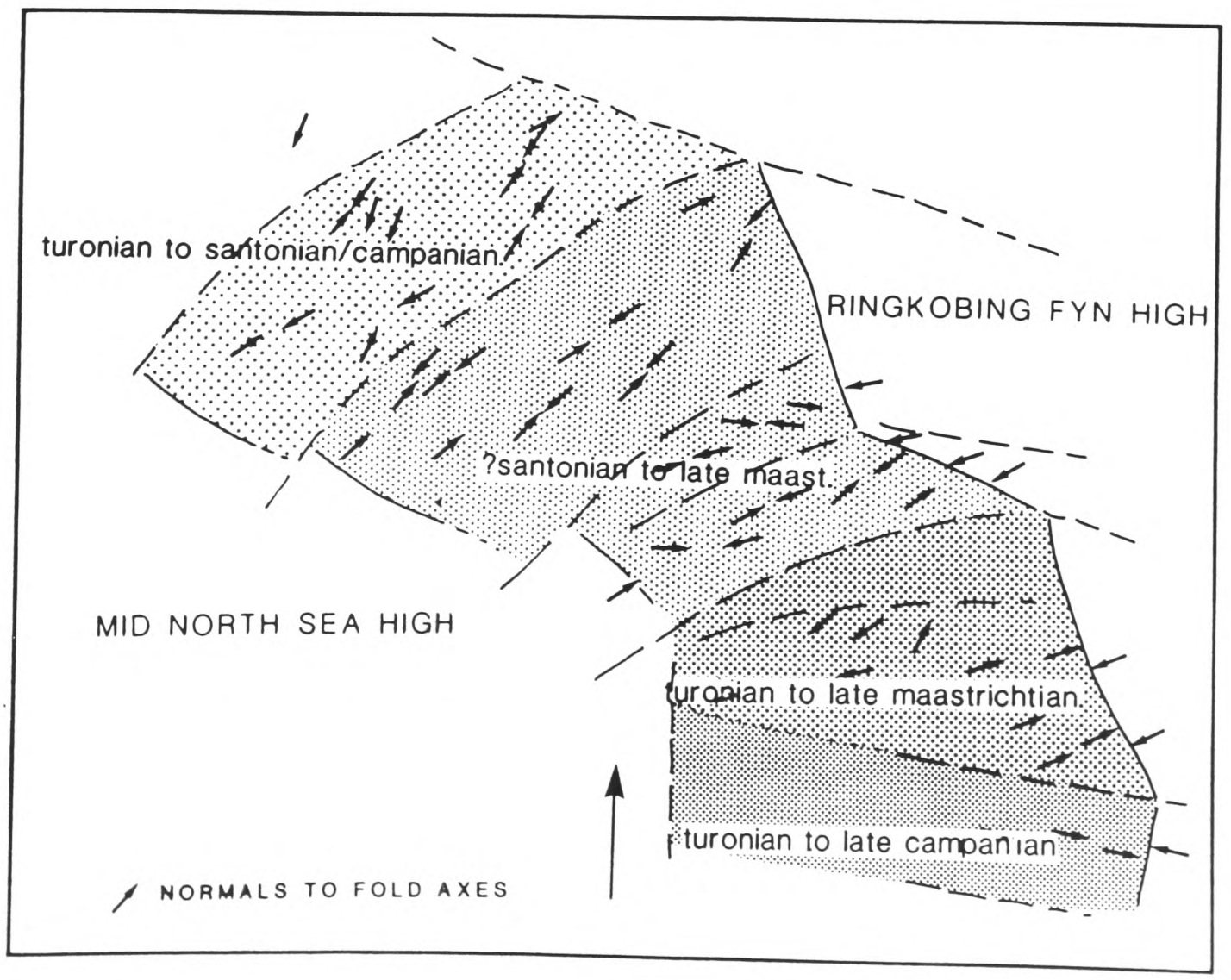


FIGURE 12

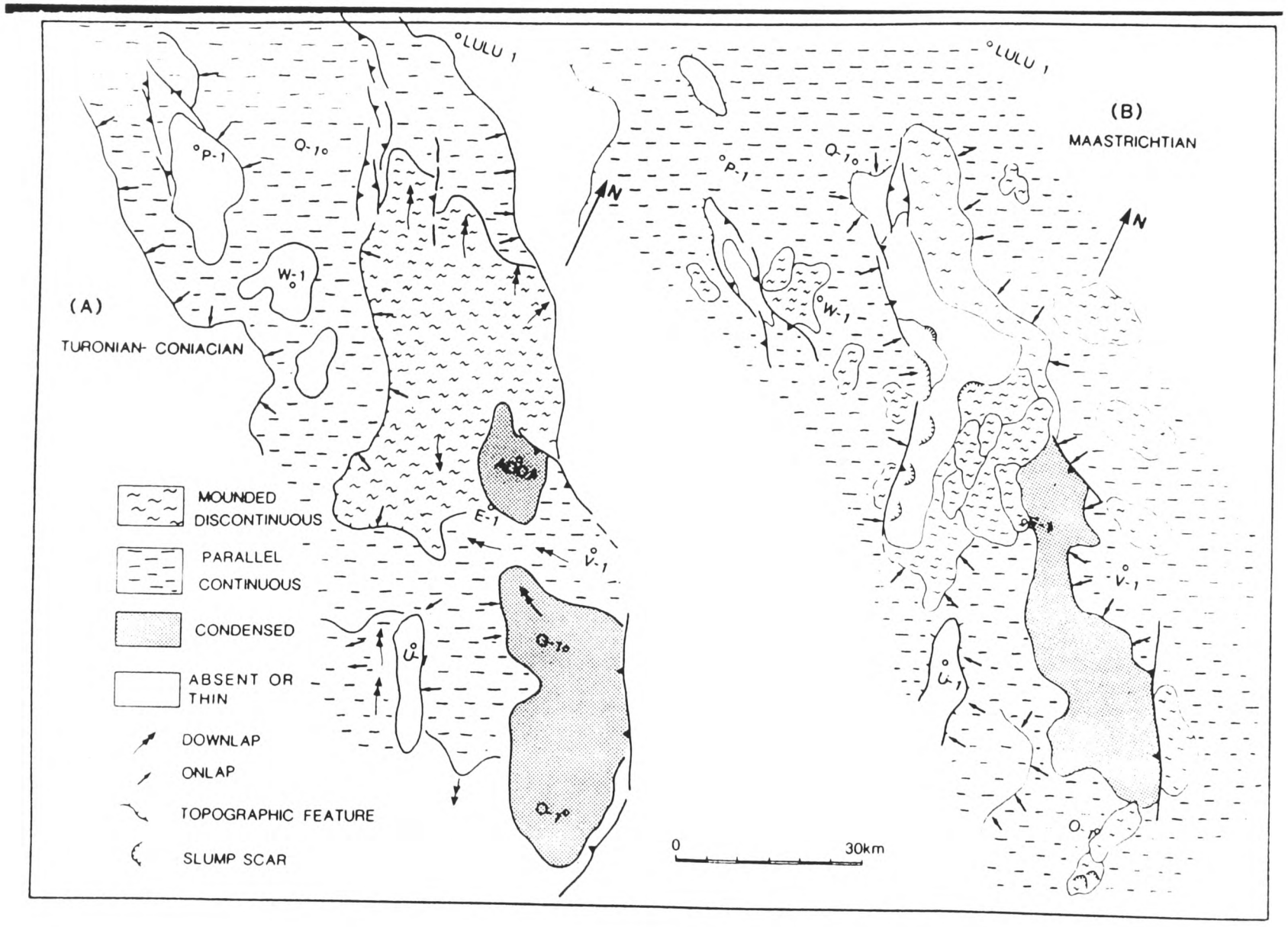

(A)
TURONIAN- CONIACIAN
(B)
MAASTRICHTIAN
N
MOUNDED DISCONTINUOUS
PARALLEL CONTINUOUS
CONDENSED
ABSENT OR THIN
DOWNLAP
ONLAP
TOPOGRAPHIC FEATURE
SLUMP SCAR
0
30km

FIGURE 13

FIGURE 14

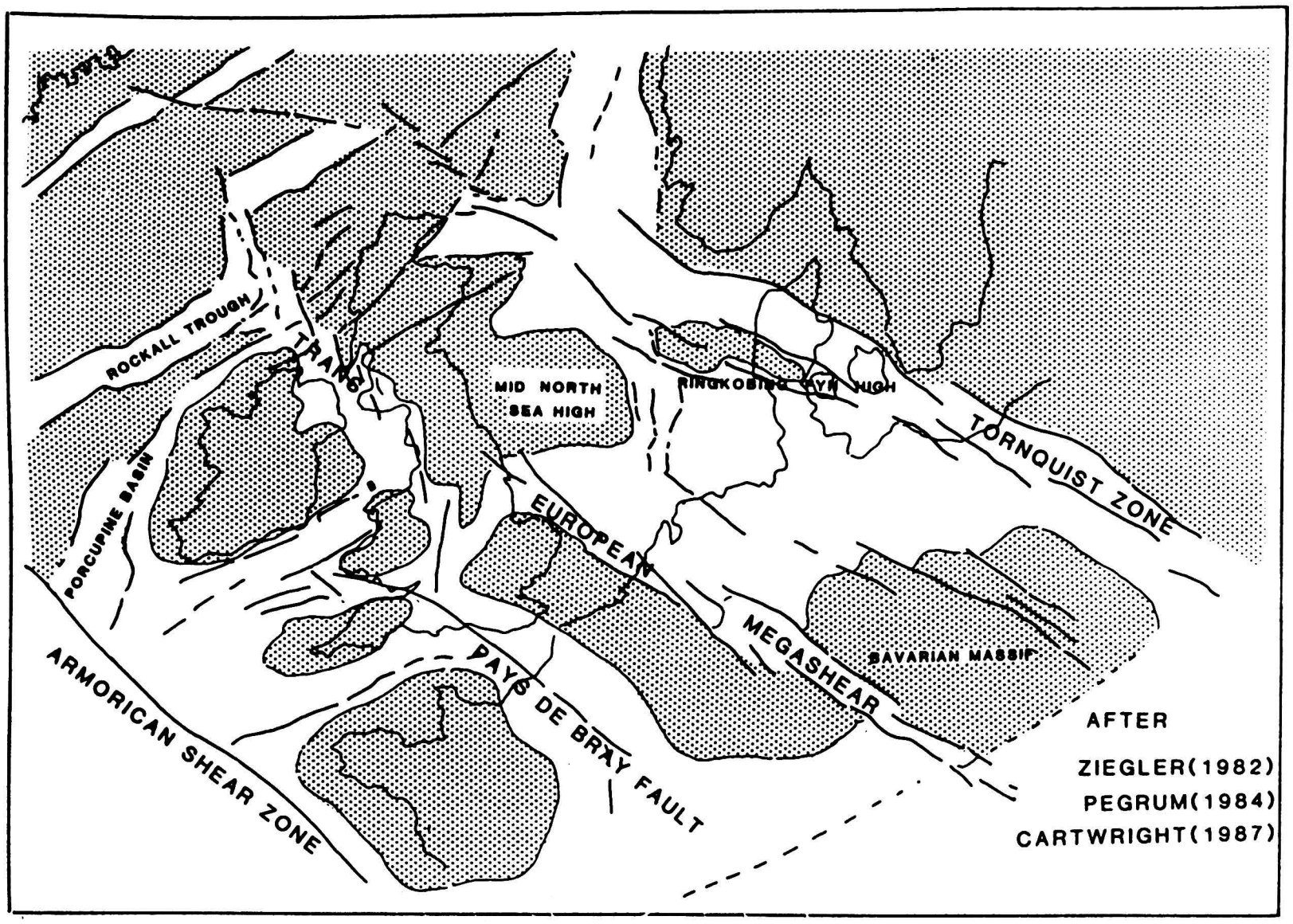
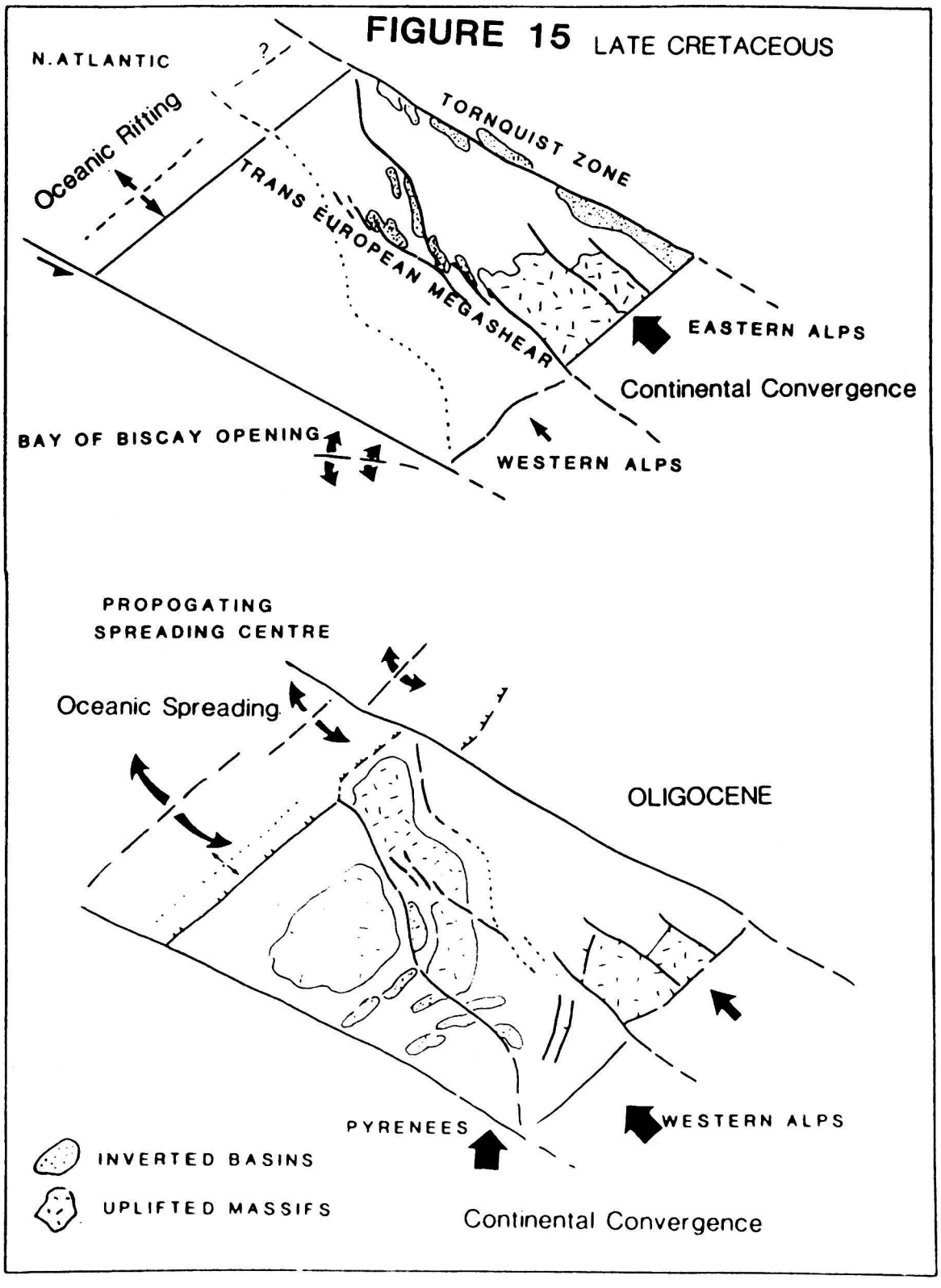


FIGURE 15 LATE CRETACEOUS



FUNDAMENTAL CRUSTAL LINEAMENTS AND TRANSVERSE STRUCTURAL ZONES IN CONTINENTAL RIFTS.

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INTRODUCTION

In the early 1920's, the origin of continental rifts or rift valleys was the subject of a heated controversy. The two main prevailing hypotheses were that of formation under tension, proposed by Professor J.W.Gregory, and formation under compression, as proposed by E.J.Wayland, who was then working for the Ugandan Survey. Wayland's theory was based on his mapping of the Lake Albert area (Wayland E.J.,1921). He noticed that the fault scarps bordering the Lake Albert Rift were staggered or offset in such a way as to suggest a segmented pattern of fault blocks linked together and bounded by transverse fault lines. He also recorded that the offset portions of the fault scarps were often sites of oil seeps or hot springs, which suggested to Wayland a fairly deep seated origin for the transverse faults. The occurrence of horizontal striae on slickensides on the offset scarp faces led him to the conclusion that the transverse faults were a set of shear failure planes which formed under a horizontal compression. From this he proposed that rift valleys were the products of horizontally inclined compressive forces. This theory was rejected in favour of Gregory's tension hypothesis, and unfortunately, the observations of the transverse structures were soon forgotten. Although Wayland's conclusions were incorrect, this does not detract from the remarkable insight he displayed in deducing the presence of the transverse faults from seemingly unconnected features on opposing margins of the lake. It is perhaps ironic that sixty years after the publication of his work on Lake Albert, observations similar to those made by Wayland are now proving to be of considerable importance in discriminating between several contrasting models for the origin of rifts.

The recent advent of seismic reflection profiling as an investigative tool has led to considerable advances in our knowledge of the structure of continental rifts. This paper is a review of one aspect of the recent developments in this field, namely that of the origin and significance of transverse structures in rifts.

FRACTURE PATTERNS IN CONTINENTAL RIFTS.

Perhaps the most striking feature of the world's major rifts is that despite their occurrence in a variety of plate tectonic settings over a variety of time intervals , they all appear to conform to an overall segmented pattern. Rifts that appear at first glance to be linear in map view are on closer inspection composed of a number of strike segments (figure 1). Each individual segment is characterised by its own structural and stratigraphic style, and neighbouring segments often differ considerably in rates of extension and fault controlled subsidence. Where a half-graben form is developed, there may be reversals in polarity across segment boundaries. In the Horn Graben (figure 2), for example, the principal rift controlling faults of the two central segments verge in opposite directions, and the reversal in polarity occurs across a broad zone of intense faulting. Individual faults within this zone have a range of orientations, but the zone as a whole is oriented transversely with respect to the rift axis. Many of the faults in the transverse zone have a strike-slip appearance on reflection seismic data, and it seems clear that a polarity reversal must necessarily involve a considerable torsional component. This example is also interesting in that the reversal is associated with considerable arching of the rift floor and flanks and the development of a magmatic centre. Other examples of polarity reversals

can be seen in the North Sea Rift, the Rio Grande Rift and the Rhine Rift (figure 1).

A number of geometric models have been proposed recently to account for the occurrence of transverse structures in extensional settings. Bally (1981) has described transform-type structures separating half-graben segments in the Basin and Range province of the western United States, and suggested that these complex zones allowed graben segments to rotate and extend at different rates. Gibbs(1984) argued that some form of cross fault system was to be expected in extensional terranes, its function being to allow 'leakage' between faults with different slip rates. He termed these cross faults Transfer Faults and drew an analogy with lateral ramps of thrust tectonics in viewing the transfer faults as contained within the 'extensional allochthon'. Gibbs favours the concept of a basal detachment to the margin fault structures, with the transfer faults terminating at the basal detachment. Rosendahl and others(1987) have introduced the concept of a 'fundamental rift unit', based on their seismic reconnaissance of the East African Rift lakes. They envisage a curvilinear arrangement of spoon shaped border faults in a repeating pattern which can take on a number of variations. All of these models share one common theme, that of an essentally accommodational role for the transverse structures. Many researchers view the transverse structures as almost a geometrical afterthought, as a passive response to extension of generally anisotropic continental crust. It is conceded that failure occurs along some line of pre-existing weakness in the crust, but does this adequately account for the consistent pattern of segmentation noted above, or is there something much more fundamental at play? Are the transverse structures simply a product of a fortuitous arrangement of weak zones relative to a prevailing

extensional stress field, or do they exert a more direct influence on rift propogation and development? The test of these two contrasting views must surely lie in the degree to which activity on the transverse zones extends beyond the immediate bounds of the extending terrane. If the transverse structures are accommodational in origin, activity along them should, as Gibbs(1984) has suggested, be confined to the rift itself. On the other hand, if activity extends well beyond the limits of a given rift, it would suggest that the transverse structures are more significant features in rift tectonics than currently appreciated.

In the following sections, two of the best documented of the world's rifts are reviewed as a basis for a discussion of the origin and significance of the transverse structures.

THE NORTH SEA RIFT.

The North Sea Rift is composed of three main segments, the Viking Graben, the Central Graben, and the Dutch Central Graben. In plan view, the three segments link to give a zig-zag pattern (figure 2). The realignment of strike at the NW end of the NW-SE trending Central Graben is manifested in a complex intermeshing of fault bounded basins and structural highs that are together referred to as the Forties Area. The added intersection of the E-W trending Outer Moray Firth Basin gives a combined appearance of a three armed rift junction, which led to early interpretations of this area as a type example of a r-r-r mantle plume induced triple junction (Whiteman, et al.,1975; Ziegler, 1982). Mesozoic volcanics are known from wells drilled in this area, and stratigraphic non-sequences in the Early Jurassic have been attributed by some authors to domal uplift and erosion resulting from the intrusion of a mantle upwarp (Ziegler, 1982).

Recent mapping of the Norwegian Sector (Pegrum, 1984) has led to suggestions that the abrupt change of strike at the Forties junction is instead related to the underlying influence of a major continental lineament, the Tornquist Zone. Pegrum (1984) has traced the lineament across the southern Norwegian continental shelf, along highly fractured linear zones, beyond the previously interpreted termination at the junction with the Oslo Rift, to intersect the North Sea Rift precisely at the Forties volcanic centre.

The Tornquist Zone is a major tectonic element in eastern Europe, separating the Fenno-Scandinavian and Russian shields to the NE from the micro-continental mosaic of Europe to the SW (Brochwicz-Lewinski et al.,1984). It has a long history of tectonic activity, ranging from the Precambrian to the Tertiary. It has been suggested that it formed a transform system during the Caledonian closure of the Iapetus Ocean, thereby accounting for the differences between the Scottish and Norwegian Caledonides (Pegrum,1984). It was a locus for sedimentary basin formation during the Mesozoic. Refraction seismic surveys conducted in eastern Europe across the Tornquist Zone show that vertical faults associated with the broad zone of deformation transect the entire crust, offsetting the Moho by several kilometres and probably continuing for considerable depths into the lithospheric mantle. The concentration of magmatic activity along the Tornquist Zone during the Late Carboniferous onset of rifting in N.W. Europe is perhaps suggestive of the depth of tectonic mobilisation of these pre-existing fractures.

The intersection of the Central Graben and the Dutch Central Graben occurs in the Danish Sector of the North Sea (figure 3). The structure of this area has been investigated recently using a 5000km. grid of reflection seismic data (Cartwright, 1987). Detailed structural mapping has shown

that the main border fault of the NNE striking rift segment undergoes a re-orientation to the NW-SE direction of the Central Graben rift segment through a series of incremental shifts in strike across WNW trending transverse fault zones. These transverse zones transect the rift and sub-divide it into a number of second-order rift segments. The intersection area is a broad corridor broken into a rhombohedral mosaic of basement fault blocks which developed either into local depocentres or structural highs.

The WNW trending transverse structural zones are best described as discontinuous arrays of faults and minor folds which offset the rift bounding structures in a systematic way and continue into the areas flanking the rift on both margins. The structural styles are indicative of oblique or horizontal components of displacement, and there are abrupt variations of both the thickness and the facies of rift-fill sequences across the zones. The transverse zones were active throughout both the extensional and compressional phases of rift evolution.

Cartwright (1987) suggested that the WNW trend adopted by the transverse zones in the intersection zone is related to a prominent WNW trending basement lineament further to the East, on the Ringkobing-Fyn High. This lineament is expressed as a narrow (10km) fault zone that runs from East Germany across Jutland to the Horn Graben off the West coast of Denmark (figure 2). It forms a major basement province boundary between the Fenno-Scandian Precambrian basement of Denmark to the North, and the Mid European Caledonides to the South (Ziegler,1982). This boundary is readily recognisable from large gravity and magnetic anomalies, and as a prominent line of weakness, it was exploited to form a structural margin to the Southern Permian Basin. Pegrum(1984), suggested that it formed as a splay to the Tornquist Zone, and this idea is supported by the significance of

the lineament as a shear zone separating two areas of markedly different crustal compositions. Furthermore, it can be traced westward into the North Sea and intersects the Horn Graben precisely at the position where the polarity of the border faults reverses (figure 1). Recent reconnaissance seismic mapping of the Ringkobing-Fyn High suggests that the lineament extends even further, from the Horn Graben across the high, to intersect the North Sea Rift at the confluence of rift trends in the Danish Central Graben. Thus it appears that this single continental lineament is at the root not only of the polarity reversal in the Horn Graben, but is also directly incident with the WNW trending corridor in the Danish Sector intersection.

In summary, it has been shown that both the major re-orientations in strike of the North Sea Rift occur at positions where fundamental continental lineaments intersect the rift. Furthermore, both intersections are loci of magmatic activity, and there is clear stuctural and magmatic evidence of tectonic activity along the lineaments over their entire lengths during the earliest phase of rift development. Given the magnitude of the vertical and horizontal dimensions of the Tornquist Zone relative to those of the Late Palaeozoic and Mesozoic pull-aparts and rifts of N.W.Europe, it is difficult to view the offsets and strike re-arrangements of the rift elements as a passive product of a tensional stress field operating on pre-existing lines of weakness. In particular, the strong spatial relationship between the centres of rift-related magmatism and the fundamental lineaments argues instead for a process of rifting based upon translation of displacement across plate interiors through interconnected networks of ancient and fundamental crustal lineaments. In acting as conduits for mantle derived magmas, the transverse fractures clearly extend to far greater depths than the rift bounding faults and they can not,

therefore, be regarded as being contained within the 'extensional allochthon'.

THE RIO GRANDE RIFT.

The Rio Grande Rift is composed of four segments, separated by a series of NE striking transverse fault zones (figures 1 and 4). The amount of extension varies markedly from segment to segment, and there is a narrowing of the rift in a step-wise fashion across each segment boundary northwards from New Mexico into Colorado.

The NE striking segment boundaries project into the Precambrian aged rift shoulders as a series of basement lineaments. The segment boundaries are complex zones of normal and strike-slip faults that offset extensional fault systems of different inclination, displacement and polarity in neighbouring segments. They were interpreted by Chapin (1978) as being the product of a " scissors-like torque in the brittle near-surface rocks and to a transverse shear at depth". In a detailed survey of the Socorro area, Chapin et al.(1978) noted a preferred alignment of rift-related magmatic centres along the trace of the Morenci Lineament, a transverse segment boundary in the southern part of the rift. Further to the North, centres of rift-related magmatic activity are seen to straddle another of the segment boundaries, the Jemez Lineament, for several hundred kilometres beyond the rift margins (figure 4). From a combination of structural mapping, aeromagnetic interpretation, and studies of heat flow anomalies and magmatism, Chapin et al.(1978) concluded that the transverse zones acted as "incipient transform faults connecting en echelon segments of the Rio Grande Rift." The strong spatial association of magmatic centres and the transverse zones argues powerfully in favour of this view. It may, in

addition, be highly significant that there is evidence from the timing of the major extrusive events associated with the onset of rifting, of a progressive northward opening of the rift (Chapin,1978).

DISCUSSION

From the preceding review of the structure of the North Sea and Rio Grande Rifts, a strong case can be made that segmentation is inherent to the initial propogation of these two rift zones, and that this segmentation was closely connected to activity on fundamental continental lineaments well beyond the bounds of the rifts themselves. Furthermore, the close association of centres of rift-related magmatism and the transverse structures bounding the rift segments suggests that the process responsible for the development of a segmented structure is intimately related to the generation and extrusion of mantle-derived magma.

These observations regarding segmentation, lineaments, and igneous activity are not merely restricted to the two examples discussed above. Transverse structures have also been described from the Baikal Rift (Logatchev and Florensov,1978), the East African Rift (Katz,1987), and the Oslo Rift (Ramberg and Spjeldnaes,1978), and, in all these cases, it appears that the transverse structures are connected to basement mobile zones or shear zones or crustal province boundaries in the adjoining flanks. In more than just a coincidental number of occurrences, the transverse structures also appear to provide the main conduits for the associated extrusives.

The widespread occurrence of transverse structures in rifts of different ages, in differing tectonic settings, indicates that segmentation is somehow fundamental and integral to processes of rifting and continental

separation. It is generally supposed that the transverse structures perform a transform function in a passive sense, and given the current preference for passive models of continental extensional tectonics, this may seem hardly surprising. From the evidence presented above, and building from those long ago observations of E.J.Wayland, a picture is now beginning to emerge of transverse structures as narrow, vertical shear zones in the mantle passing upward into more diffuse zones of discontinuous faulting in the brittle upper crust, creating as it were the impression of a lithospheric flower structure (figure 5). The magnitude of these structures, and their obvious role as conduits for magmas generated at depths often in excess of 60kms, argues compellingly for a function beyond that of mere passive accommodation. The Rio Grande Rift, with its wedge-like form narrowing northward through a series of decreasingly extended segments, is suggestive of a process of rifting dominated by shear, where the propogation into the rigid continental interior was accomplished through successive jumps across segment boundaries, once the potential energy for continued propogation had built up beyond some critical limit. Each segment represents, perhaps, a discrete pull-apart basin, linked one to another by trans-crustal or trans-lithospheric shear zones. Could this type of rhombochasm-megashear couple be more generally prevalent than is currently appreciated? There is certainly a powerful argument for this kind of mechanism to have been operative in the case of the North Sea Rift, and given the likely relative strengths of the lithosphere under an applied shear as opposed to an applied tension, it may be as well to re-evaluate current preferences. The arguments presented in this paper are admittedly circumstantial, and rely heavily on the conjectural view of the distribution of the magmatic products of rifting. Nevertheless, it is hoped

that these speculations on the active function of transverse structures will stimulate additional observations of their structure and relationship to continental lineaments and magmatism. The balance of proof may well rest in the precise timing of fracture propogation in individual segments and in the rifts as a whole, and in more specific accounts of the temporal and areal migration of extrusive activity associated with that propogation.

ACKNOWLEDGEMENTS.

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FIGURE CAPTIONS.

Figure 1. Segmentation of Continental Rifts. Many continental rifts exhibit a segmented form in which the major bounding faults (heavy lines with hachures) change strike or are offset at a number of points along the course of the rift. In the examples shown in this figure, the offsets or strike re-arrangements are also marked by zones of complex faulting oriented obliquely relative to the rift axis. These often have a component of shear, and tend to be the principal conduits for rift-related extrusive igneous rocks. In some cases (Horn, Rhine, Rio Grande), the polarity of the bounding faults reverses across the segment boundaries.

Figure 2. The North Sea Rift. The rift is composed of three main segments, the Viking Graben, the Central Graben, and the Dutch Central Graben. The zig-zag pattern has previously been explained as resulting from mantle plume induced uplift, but an alternative interpretation views the pattern as the product of differential shear along a major continental lineament, the Tornquist Zone.

Figure 3. Structural Elements of the Danish Central Graben. The area where two of the main segments of the North Sea Rift intersect is dominated by a WNW trending structural 'corridor'. The rift border faults change from a N-S strike to a NW-SE strike through a series of incremental shifts in orientation across transverse fault zones. The combination of border faults and transverse fault zones divides the area into a number of rhombohedral blocks and basins that subsided differentially throughout the Mesozoic evolution of the rift.

Figure 4. Transverse Crustal Lineaments, Segmentation and Magmatism in the Rio Grande Rift. The rift is broken up into segments by NE trending transverse shear zones (Chapin et al.,1978). These shear zones continue into the rift flanks as major crustal discontinuities. Centres of rift-related magmatism seem to be preferentially located along the trace of the NE trending lineaments, often for considerable distances beyond the rift margins, suggesting that the transverse shear zones extend to far greater depths than the rift border faults.

Figure 5. An Idealized Transverse Shear Zone. This is a schematic reconstruction of a segment-bounding shear zone. Mid-lithospheric zones of partial melting are connected to the surface by narrow and vertical upper mantle and lower crustal shear zones, splaying in the brittle upper crust into a braided, discontinuous pattern of normal and strike-slip faults. Segmentation and propogation of the rift are viewed as the product of differential shear along successive transverse lineaments. This example shows a reversal in polarity in the vergence of the main border faults.

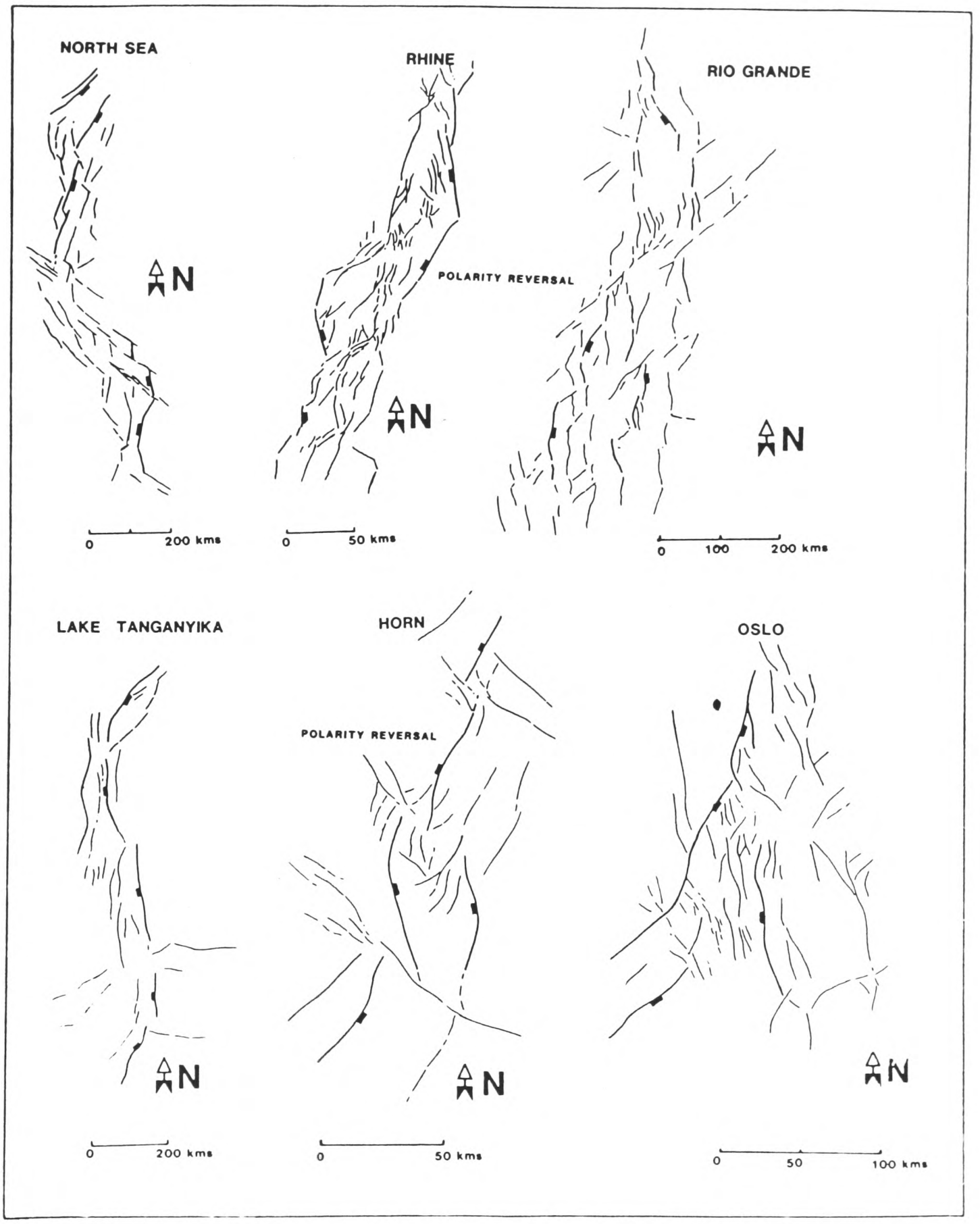

NORTH SEA
N
0
200 kms
RHINE
POLARITY REVERSAL
N
0
50 kms
RIO GRANDE
N
0
100
200 kms
LAKE TANGANYIKA
N
0
200 kms
HORN
POLARITY REVERSAL
N
0
50 kms
OSLO
N
0
50
100 kms

FIGURE 1

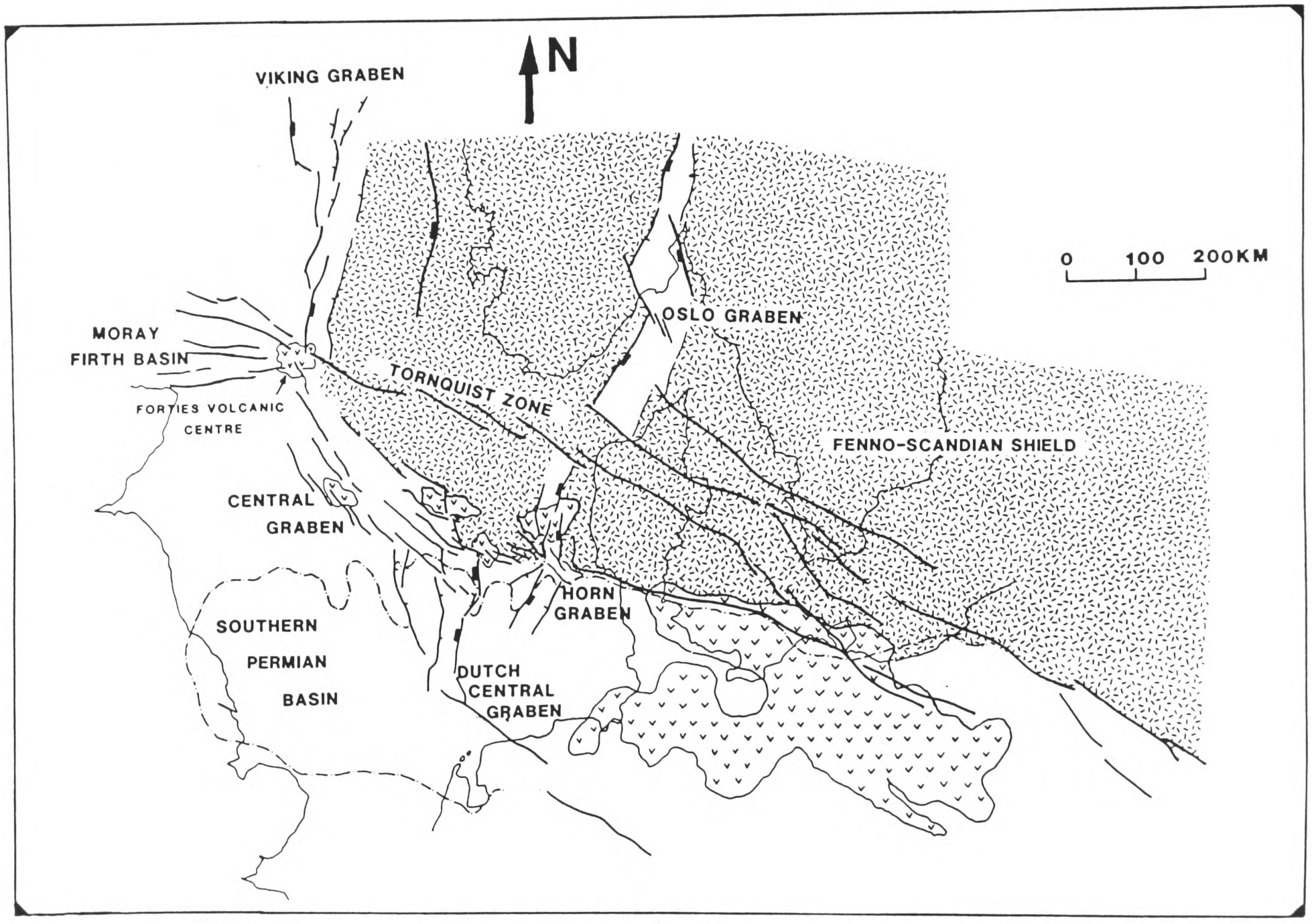

N
VIKING GRABEN
0 100 200KM
OSLO GRABEN
MORAY
FIRTH BASIN
TORNQUIST ZONE
FORTIES VOLCANIC
CENTRE
FENNO-SCANDIAN SHIELD
CENTRAL
GRABEN
HORN
GRABEN
SOUTHERN
PERMIAN
BASIN
DUTCH
CENTRAL
GRABEN

FIGURE 2

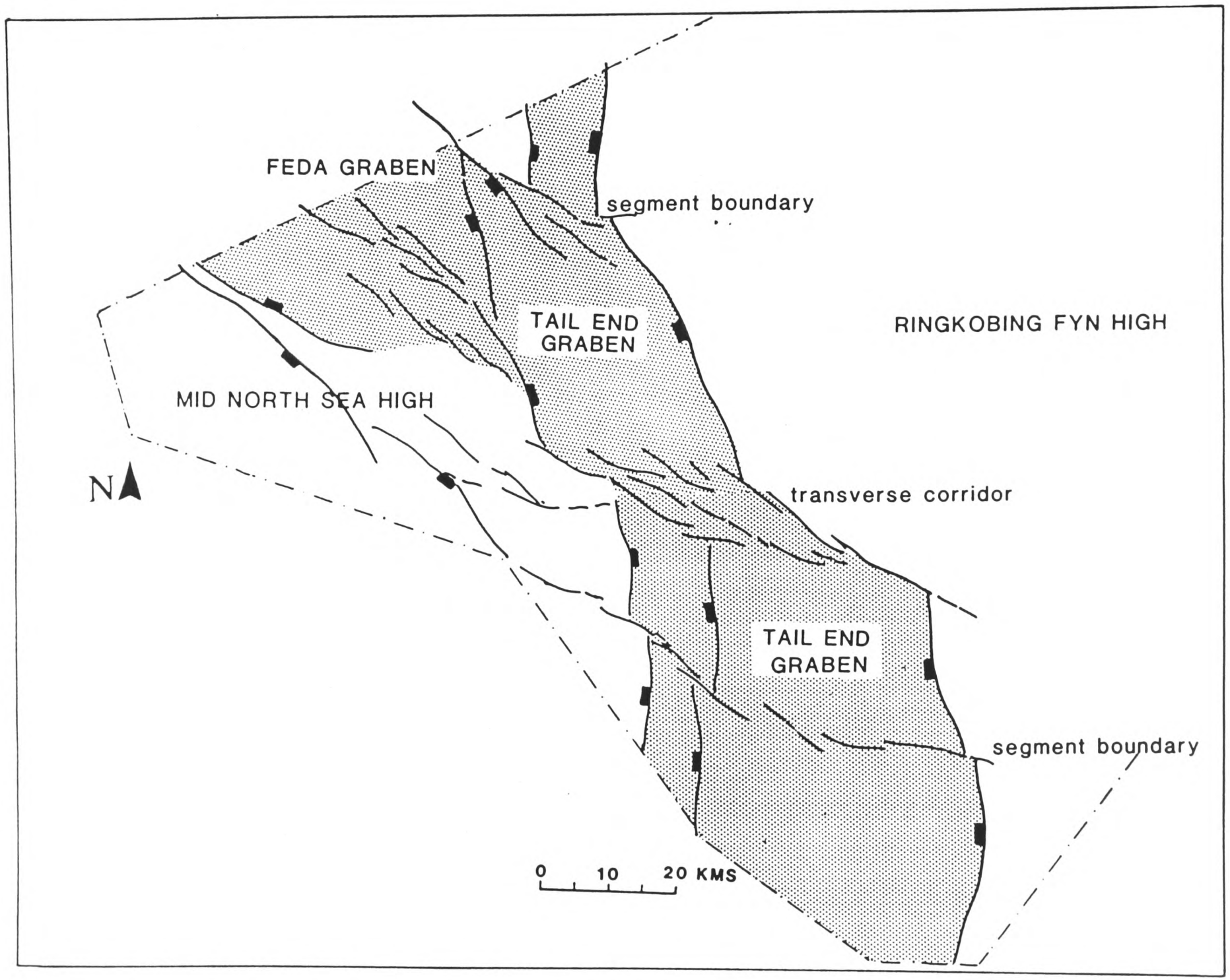

FEDA GRABEN
segment boundary
TAIL END GRABEN
RINGKOBING FYN HIGH
MID NORTH SEA HIGH
N
transverse corridor
TAIL END GRABEN
segment boundary
0 10 20 KMS

FIGURE 3

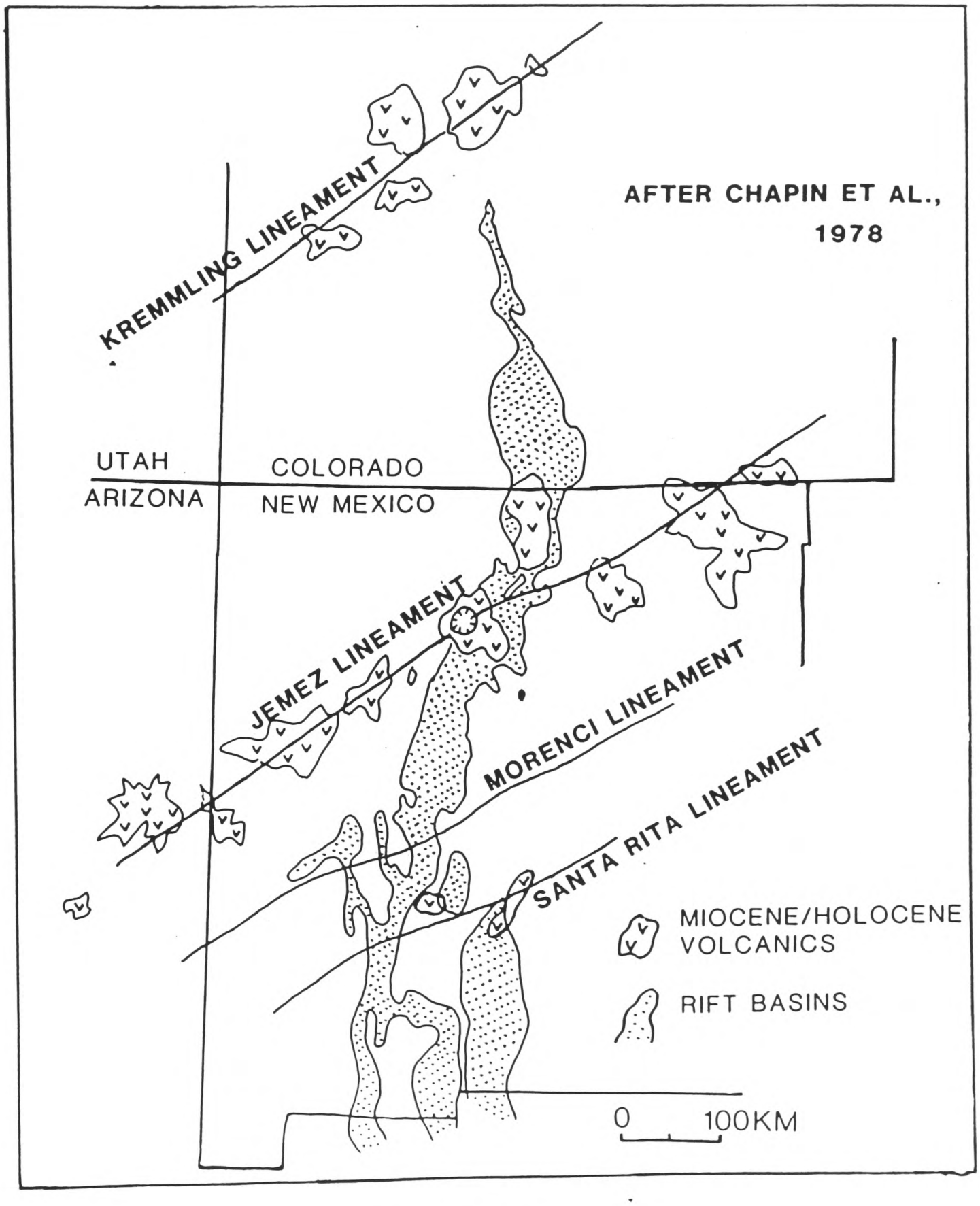

KREMMLING LINEAMENT
AFTER CHAPIN ET AL.,
1978
UTAH
ARIZONA
COLORADO
NEW MEXICO
JEMEZ LINEAMENT
MORENCI LINEAMENT
SANTA RITA LINEAMENT
MIOCENE/HOLOCENE
VOLCANICS
RIFT BASINS
0
100KM

FIGURE 4

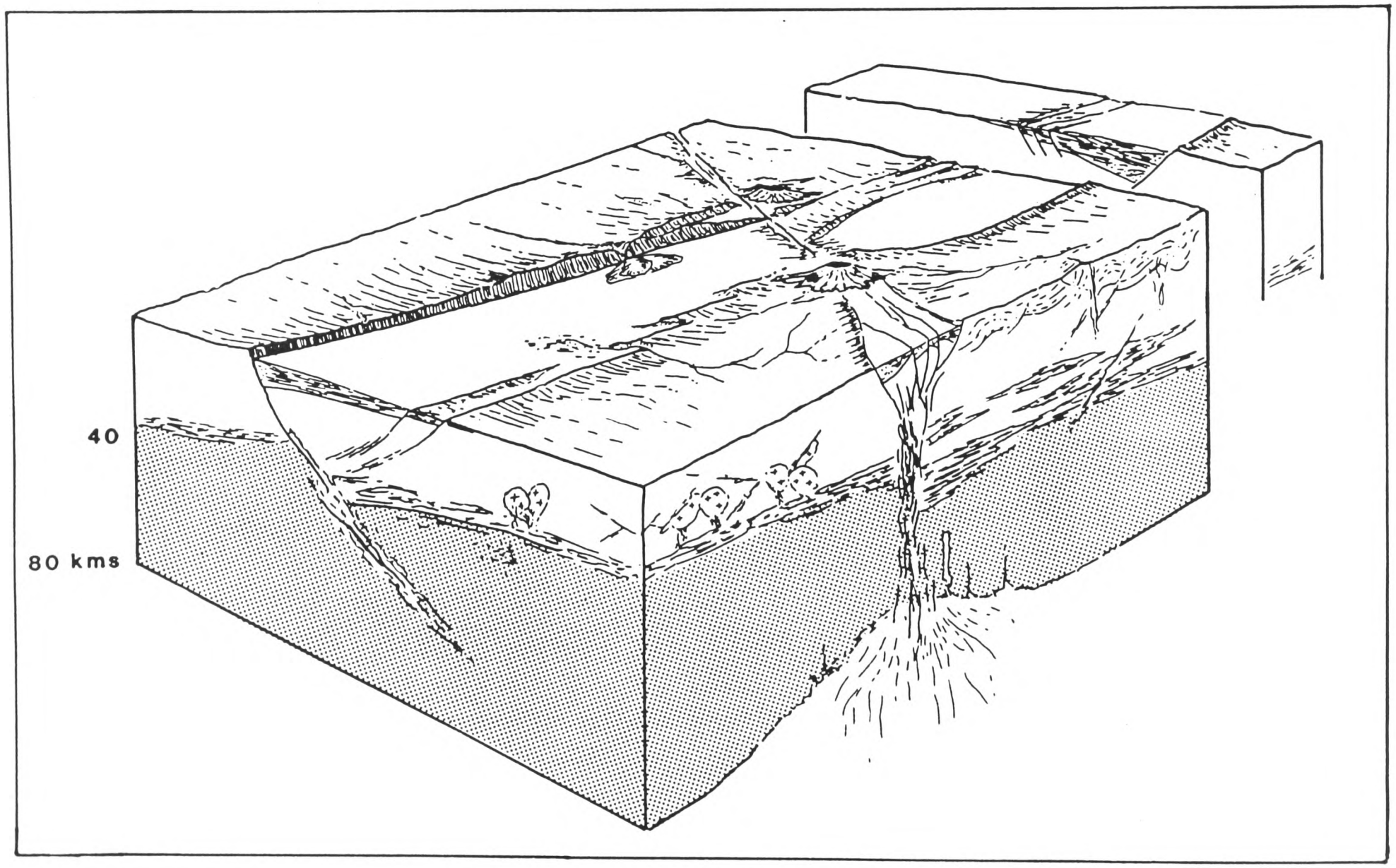


FIGURE 5