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LITHOSTRATIGRAPHY AND DEPOSITIONAL HISTORY OF THE MIDDLE TRIASSIC DOWSING DOLOMITIC FORMATION OF THE SOUTHERN NORTH SEA AND ADJOINING AREAS

VOLUME 1: TEXT, REFERENCES AND APPENDICES

CHRISTOPHER JOHN SOUTHWORTH

Linacre College and the Department of Earth Sciences,

Oxford



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DEDICATION

To my Mother

LITHOSTRATIGRAPHY AND DEPOSITIONAL HISTORY OF THE MIDDLE TRIASSIC DOWSING DOLOMITIC FORMATION OF THE SOUTHERN NORTH SEA AND ADJOINING AREAS

Christopher John Southworth, Linacre College

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ABSTRACT

Middle Triassic deposition in Northwest Europe occurred in the enclosed Germanic Basin, which extended from its connection with Tethys in eastern Poland to eastern England.

A detailed lithostratigraphic subdivision of the middle Triassic Dowsing Dolomitic Formation of the U.K. Southern North Sea and subsurface eastern England is presented, based on petrophysical logs, well cuttings and limited core. This subsurface lithostratigraphy is linked to the established outcrop lithostratigraphy of eastern England by means of a surface gamma-ray profile at Kirton Brickworks, Nottinghamshire. The outcrop lithostratigraphy is thereby accurately correlated with that of the basin centre in north Germany.

The major tectonic elements active during middle Triassic deposition in the Southern North Sea area are identified, including previously unreported differential subsidence in an extension of the Dutch Broad Fourteens Basin in the U.K. Sector.

The basinwide Hardegsen unconformity marks the base of the middle Triassic. A transgressive phase resulted first in the deposition

of lacustrine pro-delta mudstones towards the basin centre, followed by the deposition of a more extensive thin marine mudstone which formed the base of the middle Triassic over most of the U.K. Southern North Sea area. Two regressive cycles followed. Each started with deposition of the cyclic, hypersaline-marine halites (the Main and Upper Röt Halites), followed by sabkhas, then playa mudflat/lagoonal deposits. At the start of the Muschelkalk deposition, restricted marine conditions were established in the Southern North Sea area. These were followed by a further regressive sequence of hypersaline-marine halites (the Muschelkalk Halite), sabkhas, and finally playa mudstones. The establishment of continental sedimentation across the whole of the Germanic Basin marked the end of the middle Triassic.

The cyclicity within the Germanic Basin correlates with the published coastal onlap charts, indicating its origin is eustatic fluctuations in Tethys.

ABSTRACT

(extended)

Middle Triassic deposition in Northwest Europe took place in the enclosed Germanic Basin, which extended from its connection with Tethys in eastern Poland to eastern England, and from southern Scandinavia to central Germany.

The base of the middle Triassic is taken at a sequence boundary marked by the basinwide Hardegsen unconformity and, as such, the middle Triassic comprises the Röt (Upper Buntsandstein) and Muschelkalk in the basin centre, and the Dowsing Dolomitic Formation of the Haisborough Group in the U.K. Southern North Sea. Previously, only two Members have been defined within the Dowsing Dolomitic Formation: the Röt and Muschelkalk Halite Members. A new lithostratigraphic subdivision of this Formation is proposed, based on the Dutch nomenclature, which is extended from the Broad Fourteens Basin of the Dutch Sector, into the Anglo-Dutch Basin of the U.K. Sector. As this subdivision can be extended farther, onto the East Midlands Shelf in the subsurface eastern England, it is proposed that the Dowsing Dolomitic Formation (and its proposed Members) are adopted as the lowermost part of the Mercia Mudstone Group in the subsurface.

The Members of the Dowsing Dolomitic Formation are defined primarily from petrophysical logs, accompanied by drill cuttings and one core. The logs used are the gamma-ray and sonic logs and, to a lesser extent, the Formation Density (FDC) and Sidewall Neutron Porosity (SNP) logs. The previously proposed Triassic type well for the U.K. Southern North Sea, well 49/21-2, is not accepted as such for the Dowsing Dolomitic Formation, as two significant faults occur within this

sequence. The proposed type well for this Formation is 48/12-1. This latter well, lying towards the centre of the Anglo-Dutch Basin in the U.K. Sector, contains an unfaulted sequence, and has a full suite of petrophysical logs available. The cored 'Staithes-20' well of north-east England is chosen as the reference well for the thinner East Midlands Shelf sequence. It also serves as the reference well for the proposed Dowsing Dolomitic Formation of the Mercia Mudstone Group. None of the wells studied contain all of the proposed Members of the Dowsing Dolomitic Formation, and hence additional type and reference wells are proposed as necessary.

The Solling Mudstone Member, the lowermost Member of the Dowsing Dolomitic Formation, only extends westwards into the north-eastern part of the U.K. Southern North Sea. The overlying thin Riff Sandstone Member is also restricted to this same area. The thin Lower Röt Mudstone Member is the first Member to extend across the whole of the U.K. Southern North Sea, being present in both the Anglo-Dutch Basin and the East Midlands Shelf, as are the succeeding Members.

The Main Röt Halite Member, which equates with the previously defined Röt Halite Member, is present over the centre of the basin. This passes laterally towards the basin margin into, and is overlain by, the argillaceous, dolomitic, anhydritic Main Röt Evaporite Member. This Member in turn is overlain by the silty, dolomitic, anhydritic mudstones of the Intermediate Röt Mudstone Member. This sequence of halite - evaporite - mudstone is repeated, beginning with the thin Upper Röt Halite Member, which laterally and vertically passes into the Upper Röt Evaporite Member. This in turn is followed by the Upper Röt Mudstone Member. The Upper Röt Evaporite Member is less extensive than the Main Röt Evaporite Member and consequently, towards the basin margin, the

Intermediate and Upper Röt Mudstone Members are indistinguishable. In these areas they are combined as the Main Röt Mudstone Member.

Argillaceous dolomites and dolomitic mudstones comprise the overlying Muschelkalk Dolomitic Member, which equates with the Lower Muschelkalk of the basin centre. This Member is in turn overlain by a further halite - evaporite - mudstone sequence to the top of the Dowsing Dolomitic Formation. These are respectively the Muschelkalk Halite Member, the Muschelkalk Evaporite Member, and the Muschelkalk Mudstone Member. This latter Member equates with both the Upper Muschelkalk and part of the Middle Muschelkalk of the basin centre, as these are indistinguishable in the U.K. Southern North Sea. The top of the Muschelkalk Mudstone Member equates with the Muschelkalk/Keuper boundary of the basin centre. The reported biostratigraphy indicates that the individual Members of the Dowsing Dolomitic Formation are generally synchronous across the Germanic Basin.

Direct correlation between the proposed subsurface lithostratigraphy and the established outcrop lithostratigraphy of the Mercia Mudstone Group of eastern England is not possible, as the former is based on petrophysical log responses, and the latter on sedimentology. In order to combine these classifications, a 38 metre surface gamma-ray profile was measured in the lower Mercia Mudstone Group sequence at Kirton Brickworks in north Nottinghamshire. In this mudstone-dominated succession, the boundary between the more sandy Colwick Formation and the overlying Radcliffe Formation has been identified from the sedimentology. This coincides with an upward change of the gamma-ray profile to more variable values. This profile has been correlated with a near-by well, indicating that the Colwick/Radcliffe Formation boundary equates with the

subsurface Main Röt Mudstone Member/Muschelkalk Dolomitic Member boundary. Further south, near the basin margin, an Anisian age has been reported for the Colwick Formation, indicating that in this area it equates with the more basinal Muschelkalk Dolomitic Member. This Formation is hence diachronous between Kirton and the basin margin.

Basinwards, successively lower units of the Colwick Formation pass laterally into the less sandy Main Röt Mudstone Member. Hence, at outcrop, the Colwick Formation is not everywhere directly overlain by the Radcliffe Formation. This has not previously been recognised, and has lead to much misinterpretation of the lithostratigraphy around Kirton and to the north.

The higher Formations of the Mercia Mudstone Group are tentatively linked into the proposed subsurface lithostratigraphy. The Radcliffe Formation equates exactly with the Muschelkalk Dolomitic Member, the Carlton Formation equates with the Muschelkalk Evaporite Member, and the lower part of the Harlequin Formation equates with the Muschelkalk Mudstone Member.

Isopach maps of the individual Members across the Southern North Sea area define the major structural elements active during middle Triassic deposition. These are, from west to east; the East Midlands Shelf, the Anglo-Dutch Basin and the Broad Fourteens Basin. The latter, which has not previously been reported active in the Triassic, controlled the sedimentation during the deposition of the lowermost Members of the Dowsing Dolomitic Formation. The western margin of this basin forms the western limit of Solling Mudstone Member and the Riff Sandstone Member deposition in the Dutch Sector. The presence of these Members in the north-east of the U.K. Southern North Sea indicates an extension of the

Broad Fourteens Basin into this area. These Members were not deposited across the Anglo-Dutch Basin and the East Midlands Shelf.

The isopachs of the succeeding Members, which were deposited across the whole of the U.K. Southern North Sea, indicate that differential subsidence between the Anglo-Dutch Basin and the Broad Fourteens Basin gradually decreased through the middle Triassic, as the two areas increasingly acted as a single structural unit. From the time of Lower Röt Mudstone Member deposition onwards, active differential subsidence was taken up between the Anglo-Dutch Basin and the East Midlands Shelf along the Dowsing Fault Zone with, on its downthrown side, the rapidly subsiding Sole Pit Trough.

The environment of deposition of the individual Members of the Dowsing Dolomitic Formation has been determined from lateral and vertical variations in petrophysical log profiles, study of the single cored section, and from the reported literature across the basin.

Initial deposition of the middle Triassic sediments occurred on the Hardegsen unconformity surface. In the Southern North Sea area, successive Members overstepped one another towards the southern basin margin, with the Muschelkalk Dolomitic Member directly overlying the unconformity surface in the most marginal areas. From the literature, the same also appears to be the case in eastern England, around Nottingham, where the Colwick Formation (Muschelkalk Dolomitic Member equivalent) was the first middle Triassic unit to link between the Germanic Basin and the Worcester Basin.

The Solling Mudstone Member, the lowermost Member of the Dowsing Dolomitic Formation, was deposited in a lacustrine pro-delta environment during the initial transgression over the Hardegsen

unconformity surface. Deposition was restricted to the centre of the Germanic Basin. A major delta-complex entered the basin from the south in north Germany, and in the Southern North Sea area, the overlying Riff Sandstone Member may represent a thin deltaic sequence which entered the basin from the western margin of the Broad Fourteens Basin. The succeeding thin Lower Röt Mudstone Member transgressed beyond this margin to form the lowermost Member of the Dowsing Dolomitic Formation across most of the Anglo-Dutch Basin and the East Midlands Shelf. Farther east, the first marine influences in the Germanic Basin are reported from this Member.

The overlying Main Röt Halite Member was deposited as a subaqueous marine-sourced halite. Five major cycles are present in the Member, each reflecting a gradual increase in salinity from the background mudstone deposition, through thin dolomites/anhydrites, to finally halite precipitation. The Member as a whole indicates a gradual expansion, followed by a contraction in the area of halite deposition. The lowermost cycle was restricted to isolated, structurally controlled lagoons, the three following cycles were deposited in a single extensive evaporite basin, and the final cycle was deposited in a single large lagoon. Following halite deposition, the marginal sabkhas of the Main Röt Evaporite Member prograded out across the basin centre. These were followed by the alternating playa mudflat/lagoonal deposits of the Intermediate Röt Mudstone Member. This regressive sequence is further reflected within the Intermediate Röt Mudstone Member by a gradual upwards reduction in the lagoonal facies.

A similar regression resulted in the deposition of the Upper Röt Halite Member, Upper Röt Evaporite Member and the Upper Röt Mudstone Member. Hypersaline-marine conditions were re-established in the Southern

North Sea area, during the deposition of the Upper Röt Halite Member. These were succeeded by the progradation across the basin of the Upper Röt Evaporite Member sabkhas, followed by the playa mudflat/lagoonal deposits of the Upper Röt Mudstone Member. This latter Member heralds the more marine conditions of the following Muschelkalk Dolomitic Member with an upward increase in the lagoonal facies.

A four-fold subdivision of the Muschelkalk Dolomitic Member extends throughout the U.K. Southern North Sea area. Unit 1 reflects the establishment of restricted marine conditions across most of the U.K. Southern North Sea; however, towards the southern basin margin, playa mudstone deposition continued. During the brief regressive phase of Unit 2, these playa conditions extended throughout the U.K. Sector. The main transgressive phase of the Member resulted in the deposition of Unit 3 which forms the majority of the Member. During this phase, restricted marine conditions dominated throughout the U.K. Southern North Sea area. These coincided with the development of high-energy calcarenite bars in the Lower Muschelkalk of the basin centre. Playa mudstones once more dominated the Member during the deposition of Unit 4.

A major regressive phase is indicated by the succeeding Muschelkalk Halite Member, Muschelkalk Evaporite Member, and Muschelkalk Mudstone Member. The Muschelkalk Halite Member was deposited under hypersaline-marine conditions, as a series of individual evaporite cycles, in a halite basin which probably expanded then contracted during deposition of the Member as a whole. Following the halite deposition, the fringing sabkhas prograded out across the basin, followed by the playa mudstones of the Muschelkalk Mudstone Member. During deposition of the latter Member, open-marine conditions were established in the basin centre. These are not reflected in the Southern North Sea area, and hence

probably result from the opening of a second link with Tethys via southern Germany, rather than from a basinwide transgression.

The progradation of continental Keuper deposits across the whole of the Germanic Basin marked the end of the middle Triassic deposition.

The transgressions and regressions within the Germanic Basin correlate closely with the published global coastal onlap charts, indicating their origin as the result of eustatic fluctuations.

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NOTES: The list of figures, plates and enclosures are included in Volume 2.

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CHAPTER 1

CHAPTER 1

INTRODUCTION

1. THE GERMANIC BASIN - STRUCTURAL SETTING

1.1 General Basin Shape

The Triassic deposits of the North Sea and adjoining areas represent part of the east-west trending Germanic Basin which extended from eastern Poland to eastern England, and from central Germany to southern Scandinavia (fig. 1.1). It was bounded to the east by the East European Craton and to the north by the Fenno-Scandinavian High. In the North Sea area the effective northern margin was the Ringkøbing-Fyn/ Mid-North Sea High, although sediments extended north of this into the Central and Northern North Sea areas (Bertelsen 1980, Ziegler,P. 1975a, b, 1978, Ziegler,W. 1975).

To the east, the basin was separated from the fault-bounded graben of western England by the Pennine High, although a connection existed in the Nottinghamshire area during part of the middle Triassic, separating this high from the London-Brabant Massif to the south. This latter high extended southwards into continental Europe and, along with the Rhenish and Bohemian Massifs, defined the southern margin of the basin. Between these highs, Triassic sediments extended southwards into southern Germany.

At various times in the Triassic the basin was connected to the Tethys Ocean by the East Carpathian and Silesian-Moravian Gates in eastern Poland, and the Burgundy Gate in southern Germany (Bertelsen 1980).

The basin approximately coincides with the Southern Permian Basin from which it derives many of its structural elements.

1.2 Basin Structure

The forerunner of the Germanic Basin, the Southern Permian Basin, developed as a gently subsiding post-orogenic foreland basin, north of the Hercynian mountains, due possibly to isostatic rebound and foreland collapse (Ziegler,P. 1978). It has been compared in both size and position with the post-Alpine Black Sea basin (*ibid.*).

The basin continued to subside throughout the Triassic. However, this subsidence was modified by an extensional tectonic regime which heralded crustal thinning associated with the development of the Arctic North Atlantic Rift Zone, the precursor to the break-up of Pangaea and the formation of the North Atlantic in the Jurassic and Cretaceous (Ager 1975, Fisher 1984, Ziegler,P. 1975a, b, 1978, 1982a).

Subsidence associated with this extensional regime may have started in the Permian (Glennie and Boegner 1981, Jenkins and Twombley 1980), but rifting was not a major feature until the Triassic when thick sequences accumulated in rapidly subsiding graben, many of which continued as major centres of deposition until the Lower Cretaceous (Day *et al.* 1981, Fisher 1984, Glennie and Boegner 1981, Ziegler,P. 1982a). The absence of Triassic volcanism associated with these rifts supports their formation by regional extension rather than by subcrustal hotspots (Ziegler,P. 1978).

1.3 Inherited Permian Structures

1.3.1 Basin Margin Highs (fig. 1.1)

These formed between the Lower Carboniferous and the end of the early Permian (Fisher 1984, Jenkins and Twombley 1980, Ziegler,P. 1975b, 1978), from stable blocks of pre-Cambrian and Palaeozoic rocks (Day *et al.* 1981, Ziegler,W. 1975). They remained positive elements throughout the Triassic and most of the Mesozoic (Best *et al.* 1983).

The Triassic deposits overstep the margins of the Southern Permian Basin, to lie in part directly on these highs. The Mid-North Sea High/Ringkøbing-Fyn High particularly was almost totally buried during the Triassic although it still remained the effective margin to the Germanic Basin (Bertelsen 1980, Ziegler,P. 1975a, b, 1978).

1.3.2 East Midlands Shelf and Anglo-Dutch Basin

The East Midlands Shelf (fig. 1.2) was a stable area of generally slow, even subsidence throughout the Triassic. It was separated from the main basin of deposition by the Dowsing Fault Zone, a complex series of en-echelon normal growth faults which were intermittently active until the Lower Cretaceous. On the downthrown side of the Dowsing Fault Zone, the Sole Pit Trough was the site of more rapid subsidence throughout the Triassic, bounded on the west by the fault zone and on the east by a hinge zone (Day *et al.* 1980, Glennie and Boegner 1981, Ziegler,P. 1978).

To the north and east of the Sole Pit Trough, and sub-parallel with it, a further area of differential subsidence has been recognised by the present author. Whether this too originated in the Permian is unknown. It essentially coincides with the Jurassic Broad Fourteens Basin

(Ziegler,P. 1982b) and is referred to as such in this thesis (fig. 1.2).

1.4 Triassic Graben

1.4.1 The Central Graben

This, along with its northern extension the Viking Graben, is the major structural feature of the North Sea (Fisher 1984). It separates the Mid-North Sea High from the Ringkøbing-Fyn High and extends southwards into the Southern North Sea, where it separates the Anglo-Dutch Basin/Broad Fourteens Basin to the south and west from the Northwest German area to the east (Day *et al.* 1981). It becomes unrecognisable off northern Holland (fig. 1.2).

Downwarping started in the Permian but rapid subsidence did not occur until the early Triassic (Day *et al.* 1981, Jenkins and Twombley 1980, Ziegler,P. 1982a). The graben margins are normal faults which were intermittently active until the early Cretaceous (Michelsen and Andersen 1983). Generally continuous graben subsidence occurred throughout the Triassic and rapid subsidence allowed thick sequences to accumulate within the graben, compared with thinner sequences in the surrounding areas (Bertelsen 1980, Ziegler,P. 1975a).

1.4.2 Other Triassic Graben (fig. 1.2)

The Polish Trough (and its extension the Danish Sub-basin) developed during the Triassic as a fault-bounded graben overlying the Permo-Carboniferous transcurrent Tornquist Line, which separated the stable East European Craton from the fragmented Western European Platform (Surlyk 1980, Ziegler,P. 1975a, b, 1978, 1982a). Throughout the Triassic it was the site of rapid subsidence and accumulation of sediment, and

provided the first link between the Germanic Basin and the Tethys Ocean (Fisher 1984, Ziegler 1978, 1982a). Similar subsidence in the Burgundy Graben provided a southern access to Tethys later in the middle Triassic (Ziegler,P. 1982a).

The Horn Graben formed in the early Permian (Best *et al.* 1983, Jenkins and Twombley 1980) but rapid subsidence did not occur until the early Triassic and ceased in the early Jurassic (Day *et al.* 1981, Ziegler,P. 1982a). In northern Germany differential subsidence also occurred in the small Glückstadt Graben during the Triassic (Ziegler,P. 1975a, b).

1.5 Basin Margin Swells and Troughs

Along the southern margin of the basin, from the offshore Netherlands in the west to the Bohemian Massif in the east, several swells with intervening troughs occur, trending north-north-east/ south-south-west, perpendicular to the basin margin (fig. 1.2). From west to east, these are the North Netherland Swell, the Ems Trough, the Hunte Swell, the Wesser Depression, the Eichsfeld Swell and the Thuringian Depression (Ziegler,P. 1975a, b, 1982a). Farther east, the Northeast Brandenberg and Rugen Swells also occur. The North Netherland Swell is partially obscured by the post-Triassic Texel-Ijsselmeer High (fig. 2 of NAM/RGD 1980).

These swells and troughs were established in the early Triassic (Ziegler,P. 1975a, b, 1978) or possibly in the Permian (Staalduinen *et al.* 1979) and have been attributed both to active differential subsidence in the troughs (Heybroek 1974) and to local uplifts on the flanks of the

swells (Geiger and Hopping 1968, Ziegler,P. 1975a, b). They are most clearly developed in the Lower Triassic, but also extend into the Middle and Upper Triassic (Wolburg 1969).

2. PALAEOGEOGRAPHIC AND CLIMATIC SETTING

In the Triassic, the Tethys Ocean formed a large equatorial embayment in the eastern side of the mega-continent Pangaea, partially separating Laurasia from Gondwanaland (Smith and Briden 1977). Lying to the north of Tethys, the Germanic Basin was in a continental position, constituting part of Pangaea but close to the western limit of this ocean (fig. 1.3).

The absence of polar ice-caps (Parrish *et al.* 1982), and clear skies over the mega-continent, led to increased heat absorption (due to the albedo effect) and hence to high global temperatures, with the sub-tropical arid belt extending from 15° to 50° latitude (Tucker and Benton 1982). Although Pangaea drifted north during the Triassic, the Germanic Basin remained within this subtropical arid belt (moving from 15°-20° north in the early Triassic to 30°-35° north in the late Triassic). The area was affected by a prevailing east-north-east trade wind (Clemmensen 1979) blowing across the mega-continent which resulted in generally low rainfall, hot summers and cool winters over much of the North America-Eurasia region, including the Germanic Basin (Tucker and Benton *op. cit.*).

Relative to the Palaeozoic, global sea level in the Triassic was low, with the late Permian/early Triassic representing a global low-stand between the two first order cycles (Vail *et al.* 1977). Sea level rose gradually throughout the Triassic, but with several fluctuations,

which have been related to changes in the rates of sea-floor spreading (Ziegler,P. 1982a).

The deposits of the Germanic Basin reflect these generally hot arid conditions and global sea-level changes.

3. GENERAL TRIASSIC SUBDIVISIONS WITHIN THE BASIN

The Triassic gets its name from its distinctive three-fold subdivision in the Lower Saxony area of north Germany, where a sequence of light grey, thin-bedded limestones (Muschelkalk) is sandwiched between lower (Buntsandstein) and upper (Keuper) red arenaceous to argillaceous clastics (fig. 1.4). To the north and east of this area, the Muschelkalk limestones pass laterally into interbedded dolomites and mudstones, and the three-fold subdivision becomes much less obvious.

Bertelsen (1980) subdivided the Danish Triassic into four Formations on the basis of alternating regressive and transgressive phases. These are here referred to as the early Triassic regressive phase, the middle Triassic transgressive phase, the late Triassic regressive phase and the Rhaetic transgressive phase (fig. 1.4). It has long been realised that the Muschelkalk represents a transgressive phase between the continental sediments of the Buntsandstein and Keuper (Kent 1975), but it is now recognised that the argillaceous and evaporitic Upper Buntsandstein (or Röt) also represents part of this transgression.

Hence while the Muschelkalk/Keuper boundary is considered a major boundary between cycles, the Röt/Muschelkalk boundary is of subsidiary importance to that at the base of the middle Triassic transgressive phase. This lower boundary lies at a major unconformity within the Middle Buntsandstein, the Hardegsen unconformity, which occurs all

around the basin margins. Its regional significance has led several authors to place this as the major boundary within the Triassic (NAM/RGD 1980, Rhys 1974).

This thesis is primarily concerned with the detailed litho-stratigraphy and depositional history of the middle Triassic trans-gressive phase, but this is first placed in the context of the surrounding early and late Triassic regressive phases. (It must be stressed that the terms early and middle Triassic, as used in this thesis, are **not** synonymous with the terms Buntsandstein and Muschelkalk.)

3.1 The Early Triassic Regressive Phase

Following the deposition of the late Permian Zechstein evaporites, the marine access from the Arctic Ocean, via the Northern North Sea, ceased due to an end-Palaeozoic regression and possible emplacement of a major rift dome in the Greenland/Norwegian Sea area (Ziegler,P. 1978, 1982a, Ziegler,W. 1975). There is no evidence for further marine incursions from this direction during the Triassic (Bertelsen 1980, Ziegler,P. 1975).

Within the broad, flat basin inherited from the Permian, the Lower Buntsandstein (Bunter Shale Formation) was deposited on the Zechstein without obvious break, in a fluvio-lacustrine environment (Bertelsen 1980, Brennand 1975, Fisher 1984). Tectonic uplift of the basin margins was not a significant feature of the end-Permian regression, as witnessed by both the similar shape of the Southern Permian and Germanic Basins (Fisher 1984), and the limited extent of coarser clastics around the margins (Bertelsen *op. cit.*).

Coarser clastics are typical of the Middle Buntsandstein, and

close to the basin margins wadi deposits were formed, e.g. the U.K. Bunter Pebble Beds (Brennand 1975). These give way basinwards to a relatively homogeneous coarsening upwards sheet-sand complex in the west of the basin (Fisher 1984) and to interbedded sandstone and shale cycles further east (Brennand *op. cit.*). Towards the centre of the basin, mudstones dominate with sandstones thin or even absent (Würster 1960).

With the exception of Wolburg (1961, 1962), all authors have recognised four cycles (*german 'Folgen'*) within the Buntsandstein of the Lower Saxony area; named the Volpriehausen, Detfurth, Hardegsen and Solling Folgen (Boigk 1959, Richter-Bernberg 1974). Overlying a local unconformity at the basin margin (Trusheim 1961), each cycle starts with fluvial sandstones which become more distal and argillaceous basinwards (Boigk *op. cit.*), grading laterally and vertically into alluvial-flat and playa-lake deposits (Clemmensen 1979), and possibly into marine deposits in the basin centre (Bertelsen 1980, Puff and Radzinski 1980).

Sandstones prograde into the basin from all the margins, especially the south, where a major river system transported coarse clastics from the Massif Central and the Vindelician High northwards into the basin between the London-Brabant, Rhenish and Bohemian Massifs (Bertelsen 1980, Brennand 1975, Ziegler 1982a), and also from the Amorican Massif via the Worcester Graben, into the western England and Germanic Basins (Ziegler,W. 1975). Cyclicity, similar to that on the southern margin, is recognised on the northern margin of the basin where the sandstones are derived from the Fenno-Scandinavian 'Garnet Province' (Bertelsen *op. cit.*).

This cyclicity has been attributed to both purely tectonic uplift around the basin margins (Trusheim 1961, Fisher 1984, Geiger and Hopping 1968), and to tectonic movements associated with eustatic

fluctuations (Brennand 1975, Zeigler,P. 1982a). The basinwide nature of the cyclicity must favour the latter, with local uplift of the basin margin swells combined with eustatic changes, producing repeated drainage and flooding of the basin. The marginal unconformities form, and sheet-sands prograde basinwards during the more regressive phases (Ziegler,P. 1982a).

A major unconformity, the Hardegsen unconformity, underlies the Solling Folge around the basin margins (Fisher 1984, Trusheim 1961), and the regional significance of this has led several authors to place the Solling Folge within the overlying Röt (Geiger and Hopping 1968, NAM/RGD 1980), rather than in the Middle Buntsandstein (Richter-Bernberg 1974). This unconformity represents the final regressive phase prior to the middle Triassic marine transgression. Its origin is considered in detail in Chapter 6 section 2.

3.2 The Middle Triassic Transgressive Phase

This is reviewed briefly here and dealt with in detail in the following chapters.

The transgression started with the deposition of the fluvial deposits of the Solling Folge on the Hardegsen unconformity surface. This was succeeded by the hypersaline-to-marine conditions of the Röt, with access to Tethys via the East Carpathian and Silesian-Morovian Gates in eastern Poland (Bertelsen 1980). Carbonates were deposited in the east of the basin (Ziegler,P. 1982a) grading westwards into mudstones and evaporites (including the Röt Halite). Further sea-level rise resulted in the deposition of open-marine Lower Muschelkalk limestones over the east and centre of the basin, while in the west restricted marine to hyper-

saline conditions persisted. During the Middle Muschelkalk restricted marine to hypersaline conditions once again dominated across the basin, resulting in the deposition of the Middle Muschelkalk Halite.

In the Upper Muschelkalk, the access to Tethys was via both eastern Poland and the Burgundy Gate in southern Germany (Bertelsen 1980), and while open-marine limestones were once again deposited over the eastern and southern parts of the basin, evaporitic mudstones were deposited over the western areas.

3.3 The Late Triassic Regressive Phase

The late Triassic (Keuper) resulted from a eustatic regional regression which, combined with an uplift in the area of the East Carpathian Gate caused the basin to become disconnected from the Tethys Ocean (Bertelsen 1980, Ziegler,P. 1982a). Keuper environments of deposition varied between intermittent shallow seas, lagoons, delta-complexes, sabkhas and tidal flats; and similar facies prograded out across the Tethys shelf, where previously platform limestones had been deposited (Ziegler,P. 1975a, 1982a). Marine access to the basin was restricted to the Burgundy Gate. The dominant clastic input to the basin was from the north-east and east, due to uplift on the Fenno-Scandinavian High (Ziegler,P. 1978, 1982a).

The Lower Keuper is characterised by fluvio-deltaic deposits, with abundant coal in the Lower Saxony area, which pass basinwards into fine alluvial/coastal plain clastics (Bertelsen 1980, Geiger and Hopping 1968). The overlying Keuper comprises halite and evaporitic mudstones, interbedded with fluvio-deltaics, particularly towards the basin margins (Bertelsen *op. cit.*).

The Keuper Halite is the thickest of all the Triassic halites, but the lateral impersistence of individual halite beds suggests that it formed in many small saline lagoons rather than a continuous body of water. It was sourced by short-lived transgressions into the basin via the Burgundy Gate (Ziegler,P. 1982a) and possibly in part by reworking of diapiric Zechstein halite (Bertelsen 1980). Although this Zechstein halokinesis began in the middle Triassic, it did not enter the diapiric stage and affect deposition until the late Triassic (Brunstrom and Walmsley 1969, Kent 1975, Michelsen and Andersen 1983, Ziegler,P. 1982a).

The Keuper evaporites and deltaic sediments probably represent alternations between arid and more humid climates possibly induced by sea-level fluctuations (Bertelsen 1980, Ziegler,P. 1982a).

3.4 The Rhaetic Transgressive Phase

This heralds the return of open marine conditions to north-west Europe in the Jurassic, and as such is not considered further. Hence, unless otherwise stated, general references to the Triassic in this thesis do not include this final transgressive phase.

3.5 The Triassic of the Central and Northern North Sea

Although most of the Mid-North Sea High/Ringkøbing-Fyn High became buried during the Triassic, Germanic-type facies were not deposited in the area to the north except in the Danish Sub-basin (Bertelsen 1980). Over most of the Central and Northern North Sea, poorly dated Triassic basin-margin sandstones and conglomerates give way laterally to undifferentiated red mudstones, which cannot be correlated

with the sediments of the Southern North Sea area (Brennand 1975, Deegan and Scull 1977). Deposition was strongly fault-controlled resulting in highly variable thicknesses (Fisher 1984, Jenkins and Twombley 1980, Ziegler,P. 1982a). This area is not considered further in this thesis.

4. POST-MIDDLE TRIASSIC STRUCTURAL ELEMENTS

The current distribution of the middle Triassic in the study area is, in part, the result of post-depositional Cimmerian erosion, basin inversion and Zechstein halokinesis.

To locate the wells mentioned in this section, the reader is referred to Chapter 2 Section 1.1.

4.1 Cimmerian Unconformities

Periodic uplift and differential subsidence of the graben and horsts, plus temporary lowering of the erosive base level, led to distinct periods of erosion on the basin margins and structural highs, between the late Triassic and early Cretaceous (Ziegler,P. 1982a). The result was the total erosion of the middle Triassic from parts of the basin margin (particularly the Mid-North Sea High), and from structural highs bounding the Central Graben. The originally continuous Germanic Basin is hence now subdivided into several isolated structural sub-basins (fig. 1.5).

On the western margin of the Central Graben, the Cleaver Bank Uplift extends north-south from the Mid-North Sea High to the London-Brabant Massif, approximately along the median line of the U.K. and Dutch Sectors, completely separating the middle Triassic in the two areas. On

the eastern margin of the Central Graben, the situation is more complex. An unnamed high extends south from the Ringkøbing-Fyn High to the north Netherlands, where it merges with the Texel-Ijsselmeer High. This latter high and the Cleaver Bank High almost meet, effectively splitting the Dutch North Sea into two sub-basins. To the east of the Texel-Ijsselmeer High, no information about post-Triassic structural features has been available to the author. The various sub-basins are referred to in this thesis as the U.K. Sector, Southern Dutch Sector, Northern Dutch Sector and the Northwest German areas respectively (fig. 1.5).

Three distinct phases of Cimmerian erosion occur, but evidence of the early and middle Cimmerian unconformities is only locally preserved below the much more extensive late Cimmerian unconformity.

4.1.1 Early and Middle Cimmerian Unconformities

The early Cimmerian unconformity marks the base of the Rhaetic transgressive phase. Erosion was relatively mild and restricted to the basin margins (Surlyk 1980, Ziegler,P. 1978), with continuous deposition across the Keuper/Rhaetic boundary in the basin centre (Ziegler,P. 1982a). The unconformity has been recognised cutting down into the middle Triassic by the author in four wells close to the London-Brabant Massif ('Hunstanton', 'Saxthorpe', 'South Creake' and 48/29-5). In these wells the uppermost Member of the Dowsing Dolomitic Formation is partially eroded (encl. Map 16).

The middle Cimmerian unconformity occurs in the middle Jurassic, affecting the Mid-North Sea High and Ringkøbing-Fyn High in particular (Bertelsen 1980), and coincides with the end of rifting in the Horn Graben (Ziegler,P. 1978). It has not been recognised by the author in any of the wells containing a middle Triassic intersection, but is

reported in well 38/22-1 on the Mid-North Sea High.

4.1.2 Late Cimmerian Unconformities

This is not a single unconformity, but a series of local breaks occurring in the late Jurassic/early Cretaceous, caused by tectonic pulses combined with a major end of Jurassic sea-level fall (Day *et al.* 1981, Fyfe *et al.* 1981, Heybroke 1974, Rawson and Riley 1982, Ziegler,P. 1978). Unlike the early and middle Cimmerian unconformities, it affected not only the basin margins, but also large parts of the basin centre as well. The Cleaver Bank High and the Texel-Ijsselmeer High are essentially late Cimmerian features (Brennand 1975). Continuous deposition over the Jurassic/Cretaceous boundary was restricted to only the most rapidly subsiding areas like the Sole Pit Trough.

In the vast majority of wells examined by the author, in which the middle Triassic is totally or partially eroded, Lower Cretaceous sediments directly overlie the unconformity (see Appendix A, Table 2).

4.2 Basin Inversion

Many of the areas which accumulated thick sequences of sediments throughout the Triassic and most of the Mesozoic, were uplifted and eroded during the late Cretaceous and early Tertiary, due to reversed compressive movements on the basin-margin faults associated with the Alpine orogeny (Jenkins and Twombley 1980, Ziegler,P. 1982b). Inversions occurred in the Lower Saxony Basin, offshore Netherlands and the Central Graben. In the Sole Pit Trough, up to 1500 metres of uplift may have occurred (Glennie and Boegner 1981).

In two wells examined by the author, the middle Triassic

succession is affected by this basin inversion. Both lie in the Sole Pit Trough. In well 47/5-1, the eroded top of the Dowsing Dolomitic Formation sits about 1,100 metres higher than the top of the Formation in the surrounding wells. (The eroded top is at 486 metres sub-sea, compared with 1697 metres in well 47/3-1 and 1519 metres in well 48/6-5; Appendix A, Table 2.) Well 48/11-1 shows both a repeated (reverse faulted) sequence within the lower Dowsing Dolomitic Formation as well as normal faulting higher in the Formation (fig. 1.6). This is considered to be related to Sole Pit basin inversion, during which some normal faults were reactivated with a reverse movement. This is the only well examined which shows reverse faulting; all other faulted middle Triassic intersections show a loss of section i.e. normal faulting (wells 42/26-1, 47/15-1, 49/21-2 and 53/1-3).

4.3 Zechstein Halokinesis

Locally the middle Triassic sequence is missing due to Zechstein salt piercement. As such structures underlie potential hydrocarbon traps, several wells examined have no middle Triassic intersection. Excluding those wells in the areas of Cimmerian erosion, the middle Triassic is totally absent due to diapirism in wells 42/28-1, 48/3-1, 48/10-1, 49/1-1, F/9-1 and F/14-2, and is partially missing in wells 42/13-1, 47/9-3, 49/23-4 and K/17-2. These wells are marked on enclosure Maps 1-16, see for example encl. Map 1.

5. AIMS OF THE THESIS

This thesis considers the middle Triassic, primarily between

eastern England in the west and eastern Holland in the east, with special reference to the East Midlands Shelf, the Anglo-Dutch Basin, and the proposed Broad Fourteens Basin (the areas where the greatest amount of data is available). A limited amount of well data has allowed the discussion to be extended into the Northern Dutch Sector and into the Northwest German area. This study area is shown on fig. 1.2.

Within the study area the primary aims of the thesis are two-fold; to refine the lithostratigraphy of the U.K. Sector of the Southern North Sea and subsurface eastern England, and to consider the depositional history of the various lithostratigraphic units in the light of known eustatic and tectonic events affecting the basin. In approaching these objectives, several subsidiary aims presented themselves.

5.1 Lithostratigraphy

The Triassic of the U.K. Southern North Sea is divided into two Groups, the lower Bacton Group and the upper Haisborough Group, and the latter is then divided into Formations based on the relative percentages of dolomite, halite and anhydrite (Rhys 1974). The lowermost of these Formations, the Dowsing Dolomitic Formation, equates with the middle Triassic transgressive phase (fig. 1.4). Only two Members have previously been proposed in the Formation, the Röt and Muschelkalk Halite Members. In 1980, a detailed lithostratigraphy for the Triassic of the Dutch Sector was proposed by the Nederlandse Aardolie Maatschappij B.V. and the Rijks Geologische Dienst (NAM/RGD 1980), in which not only were the Röt and Muschelkalk Formations recognised separately, but individual Members (including the halite Members) were traced from the Lower Saxony area into the Southern North Sea.

The prime lithostratigraphic objective of this thesis was hence to extend the Dutch subdivisions from the Anglo-Dutch/Broad Fourteens Basins in Dutch waters to the same basins in the U.K. Sector, and thereby to refine the lithostratigraphy proposed by Rhys (1974).

As it became evident that this detailed subdivision could also be extended onto the East Midlands Shelf under eastern England, a second objective emerged, i.e. to correlate these lithostratigraphic units with those proposed for the outcrop around Nottingham. The two lithostratigraphic classifications are not directly comparable. The outcrop units are divided on sedimentary criteria, while the subsurface subdivision is based primarily on gamma-ray and sonic petrophysical logs. In order to compare the outcrop to the subsurface, a method for measuring a surface gamma-ray profile was devised, and the results compared with the subsurface gamma-ray logs. This allowed a direct comparison of the two lithostratigraphic classifications.

5.2 Depositional History

The aims have very much been moulded by the nature of the data available, which have mostly been from subsurface petrophysical logs, one core in eastern England, and limited outcrop studies. These data have allowed the gross thickness and lithological variations of individual Members within the study area to be determined. These in turn have been combined with the basinwide literature to produce a structural and depositional model for each Member throughout the basin as a whole. These have then been combined to develop a structural/eustatic model for the middle Triassic in the basin in general and the study area in particular.

6. LAYOUT OF THE THESIS

Chapter 1 Introduction to the general geological setting of middle Triassic deposition, and to the aims and layout of the thesis.

Chapter 2 Introduction to the nature of the data available and limitations placed on its interpretation.

Chapter 3 Proposed refined middle Triassic lithostratigraphy of the U.K. Southern North Sea and subsurface eastern England.

Chapter 4 Correlation of the outcrop lithostratigraphy of the Nottinghamshire area with the newly proposed subsurface litho-stratigraphy by means of a surface gamma-ray profile.

Chapter 5 Discussion of the active middle Triassic structural elements in the Southern North Sea area.

Chapter 6 Aspects of the depositional history of the the various proposed Members of the Dowsing Dolomitic Formation, and a synthesis of the middle Triassic development throughout the Germanic Basin.

CHAPTER 2

CHAPTER 2

DATA AVAILABLE

This is primarily from subsurface well data, supplemented by outcrop studies. No seismic information has been available for use in this thesis.

1. SUBSURFACE WELL DATA

This is from wells drilled by the oil industry, both onshore and in the North Sea, plus wells drilled for water and mineral exploration onshore. The data are primarily from petrophysical logs, supplemented by core and drill cuttings.

Over much of the study area, the middle Triassic overlies the Permian 'Rotliegendes Sandstone', the main gas reservoir of the Southern North Sea, and hence many wells have penetrated the sequence. Unfortunately oil-industry interest in the middle Triassic is minimal, and therefore the quantity and quality of the data can vary considerably from well to well.

The offshore policy in both the U.K. and Dutch Sectors, of 'releasing' well data to the respective government bodies after a limited period, has made this research possible. Almost all the offshore data comes from such 'released' wells. Onshore in the Netherlands and Germany, there are no 'released' wells and hence confidential data have been obtained from individual oil companies. In order to protect the confidentiality of such data, these wells have been renamed, no absolute depths are quoted, and their positions on maps and diagrams are approximate.

1.1 Quadrants, Blocks and Well Names

In order to locate wells mentioned in this thesis, it is necessary to describe briefly the standard well numbering system used in the offshore areas.

The North Sea is divided into quadrants by the lines of latitude and longitude. In the U.K. Sector, these quadrants are given a number (35 to 53 in the study area), and in the Dutch Sector a letter (A to Q). Each quadrant is then divided into Licence Blocks (30 per quadrant in the U.K. Sector, and 18 per quadrant in the Dutch Sector), and these are numbered, left to right and top to bottom, from 1 to 30 (or 1 to 18). Offshore wells are named by reference to the quadrant, block, and well number as follows: 48/22-2 (U.K. Sector), K/14-1 (Dutch Sector).

Although the true (or altered) names of onshore wells are shown on the maps and diagrams this has not been practical for offshore wells. All maps however show quadrant and block boundaries (e.g. encl. Map 1). The number (or letter) of each quadrant is shown on the maps and the block number can be determined by counting from left to right and top to bottom. The number of the well within the block is shown on the map. The full well name can hence be determined (fig. 2.1). The few offshore wells referred to in the German and Danish North Sea are named in full on the relevant maps.

It is often the policy when referring to wells, to prefix the name with that of the operating company (e.g. Mobil 43/21-1). For brevity, this policy has not been followed in this thesis, the operating companies for each well are, however, listed in Appendix A, Table 2.

1.2 Petrophysical Logs

These are continuous response v. depth graphs determined from various probes run down-the-hole. They provide the prime source of data within the study area. The main logs for correlative purposes are the gamma-ray and sonic logs, and for more detailed petrophysical studies these are joined by the Formation Density and Neutron Porosity logs. Not all these logs were available for all the wells. While gamma-ray logs were ubiquitously available, and sonic logs almost so, Formation Density and Neutron Porosity logs were rarely available. For purely logistical reasons, access to the latter logs was restricted to the U.K. Sector.

In total 271 wells have been used in this thesis. For 233 of these, the petrophysical data came from original oil company logs (of considerably variable quality) which were available as paper prints on a vertical scale of either 1:500 or 1:1000. For the remaining wells, data was primarily from petrophysical logs presented in various papers. These wells were used for those areas where limited other data were available. These are: the Nottingham area (Balchin and Ridd 1970), onshore Netherlands (Gdula 1983, van Lith 1983), north Germany (Boigk 1959, Kelch and Paulus 1980, Philipp 1960, Trusheim 1971), and the Danish area (Bertelsen 1980, Michelsen and Andersen 1983). In all cases, the interpretation of these data are the present author's and may be at variance with those given in the publication. Details of all the wells used are given in Appendix A, Tables 1 and 2.

The following description of the petrophysical tools and responses is based on Schlumberger (1972a, b). Detailed descriptions of the geological aspects of well log evaluation are given in Asquith and Gibson (1982) and Rider (1986).

1.2.1 The Gamma-ray Log

The gamma-ray tool measures the natural radioactivity of the formation. It can be run in both open and cased holes, although in the latter, the response is somewhat attenuated by the metal casing. The log is primarily used for well to well correlation, and as a guide to identifying clayey formations. Correlation is based on the recognition of similar log profiles in different wells, rather than the matching of absolute values. In this way it is possible to match the attenuated responses in cased wells with the full responses of uncased wells (fig. 2.2).

In general shales and clays give a high gamma-ray count, while dolomites, limestones and sandstones have low gamma-ray values. Hence, as the percentage of clay in a formation increases, the gamma-ray log value increases, and, in a simple two component system (e.g. sandstone/shale), the amount of clay can be calculated from the gamma-ray log reading (Asquith and Gibson 1982, p.91). However, in the complex lithologies of the middle Triassic, only qualitative estimates of the amount of clay can be made from the log. The gamma-ray log alone cannot be used to distinguish between sandstone, dolomite, limestone, halite and anhydrite, all of which exhibit similar low radioactivity.

Gamma-ray logs are shown on all correlative sections, to the left of the vertical axis representing the well column. The gamma-ray values are in standard API (American Petroleum Institute) units and increase from left to right. Boundaries between beds are picked at the point half-way between the adjoining maximum and minimum values (see for example the top of the Main Röt Evaporite Member in fig. 2.2).

1.2.2 Sonic Log

The sonic tool measures the acoustic properties of the formations encountered. The log is recorded in units of Interval Transit Time (Δt), defined as the time taken (in micro-seconds) for a compressional sound wave to travel through one foot of formation. Once the correction for pore fluid (Δt_f) is made, Δt is primarily dependant on matrix lithology (Δt_{ma}) and porosity ($\emptyset$). The sonic log measures only the primary intergranular porosity, as the sound wave passes around, rather than through secondary vugs and moulds.

The log is very useful for correlative purposes (between uncased wells), especially in the argillaceous middle Triassic succession where it is often more sensitive to lithological variation than the gamma-ray log. This is because of the large difference between the low Δt_{ma} values of dolomite, anhydrite and halite, compared with the much higher Δt_{ma} values of clay (fig. 2.3). As anhydrite and halite have very low porosities, the measured Δt is very close to the calculated Δt_{ma} values of 50 μ.sec/ft (anhydrite) and 67 μ.sec/ft (halite). Hence these minerals can often be identified directly from the sonic log, especially the distinctive Röt and Muschelkalk Halites (the former is seen in fig. 2.3).

Occasionally in the middle Triassic, borehole conditions are very poor, and 'cycle skipping' occurs. This is recognised on the log by abrupt changes to very high Δt values (Schlumberger 1972a, p.37), and all logs over such zones are considered suspect. Cycle skipping is indicative of soft, easily caved lithologies.

Where available, the sonic log is shown along with the gamma-ray log on all correlative sections, and is always located to the right of the vertical axis representing the well column, with Δt increasing

from right to left.

1.2.3 Formation Density Log

The Formation Density (Compensated), or FDC log, measures the electron density of the formation, which is related to the bulk density (ρ_b). This in turn depends on the matrix density (ρ_{matrix}), the amount of porosity (Ø) and the pore fluid density (ρ_f). The instrument automatically corrects for borehole irregularities. In the FDC logs used, this borehole correction never exceeded 0.2 gm/cc, the value above which the log would be considered invalid (Asquith and Gibson 1982, p.67).

The FDC logs used are shown on encl. Wells A to F, overlain on the Neutron Porosity logs and are scaled in grams per cubic centimetre, with ρ_b increasing from left to right.

1.2.4 Neutron Porosity Log

Several neutron tools exist, all of which measure the hydrogen ion concentration in the formation. As this is mainly concentrated in the water (or hydrocarbons) filling the pores, the log effectively measures the porosity of the formation (although in clayey formations chemically bound hydrogen is also read by the tool as porosity (Stick and Hartline 1962)). Neutron Porosity logs are calibrated for a particular matrix lithology (usually limestone), and when the log is run in that lithology the Neutron Porosity ($Ø_N$) equals the true porosity (Ø), but in all other lithologies a correction factor must be applied.

The restriction of this thesis to 'released' wells has meant that only the older Sidewall Neutron Porosity Log (SNP) has been available (Tittman *et al.* 1966). Unlike the more modern Compensated Neutron Log (CNL), the SNP tool cannot be used in cased holes and has to

be run separately from the FDC tool. Slight depth discrepancies may hence occur when the FDC/SNP logs are overlain (section 1.2.5).

The available SNP logs are shown on encl. Wells A to F, overlain on the FDC logs, and are scaled in Limestone Porosity Units (LPU) with values increasing from right to left.

1.2.5 The FDC/SNP Overlay

Essentially, the overlay offers a quick-look lithology interpretation (Prissholm and Michelsen 1979). The SNP log is scaled in Limestone Porosity Units (LPU), and the FDC log in gm/cc. Calibration is as follows: The ρ_{ma} for limestone is 2.71 gm/cc, and this (by definition) equals zero LPU. The ρ_f (i.e. 100% porosity) for salt-based drilling mud is 1.1 gm/cc, and hence, by linear interpolation, 0.16 gm/cc equals 10 LPU (this is rounded up to 0.5 gm/cc equals 30 LPU). Once the FDC/SNP logs are thus compatibly scaled, they are overlain with $\emptyset_N$ = 0 LPU, equal to ρ_b = 2.71 gm/cc. The resulting overlays are shown in encl. Wells A to F. The location of these wells is shown on fig. 2.4.

In a pure limestone the FDC and SNP curves will overlie one another, and the value in LPU will be the true porosity. In all other lithologies there will be a separation between the two curves, which can be interpreted in terms of lithology. Of importance are; (a) the direction of separation between the curves, (b) the amount of separation, and (c) the absolute value of the SNP log. When the SNP curve lies to the left of the FDC, this is termed a negative separation, and when it lies to the right, this is a positive separation. Figs. 2.5 and 2.6 show the theoretical responses, and fig. 2.7 shows a detail from encl. Well A.

The middle Triassic halites, with their large positive separation are easily recognised on the overlay (fig. 2.7). All the other

common lithologies found in the middle Triassic have a negative separation on the overlay. Mudstone dominated zones show the largest negative curve separation, and highest absolute SNP values, while dolomite and anhydrite dominated zones show a generally smaller curve separation and much lower absolute values.

Examination of encl. Well A shows that the FDC/SNP overlay supports the lithostratigraphic subdivision based primarily on the gamma-ray and sonic logs.

1.2.6 Log Profiles

The following terms are used to describe log profiles. Examples are shown on fig. 2.8.

(a) Blocky - fairly constant log values

(b) Serrate - highly variable log values

(c) Funnel-shaped - decreasing upwards log values

(d) Bell-shaped - increasing upwards log values

The FDC scale increases away from the well column and hence (c) and (d) are reversed for this log.

1.2.7 The MID-Plot

Lithological and porosity information for a particular horizon can be obtained by cross-plotting the values from the various petrophysical logs. Two log cross-plots (sonic/FDC, sonic/SNP, FDC/SNP) provide data on lithology and porosity in 'clean' formations (Schlumberger 1972a), however, for detailed lithology determinations, the effects of porosity are removed by cross-plotting all three of the above logs.

Two such cross-plots exist, the M-N Plot (*op. cit.*, p.73) and

the MID-Plot (Schlumberger 1974, p.25). The latter plot has been used to produce the detailed lithological interpretations shown on encl. Wells A and C to F, as it was found to provide the best resolution between the main constituents of the argillaceous Dowsing Dolomitic Formation (anhydrite, dolomite, quartz and clays).

1.3 Core

Core is rare in the middle Triassic. The author knows of no oil-industry wells in which the sequence has been cored. The only fully cored middle Triassic succession in the Southern North Sea area is in the 'Staithes-20' well (Cleveland Potash Co. Ltd.) of north-east England (fig. 2.4). The core, which is almost complete through the middle Triassic, has been examined by the author at the former B.G.S. Kippax Rock Store, near Leeds. Access to the core was however restricted: Firstly, it was not slabbed, and secondly, sampling was restricted to loose chips. As a result, study of the core was confined, in the main, to an 'in situ' visible description. The core has also been briefly described by Woods (1973). Core photographs are shown on Plates 3.1. to 3.24. These Plates are arranged in stratigraphic order within the well, rather than in consecutive order within the text.

The Staithes area sits on the East Midlands Shelf and hence the sequence in the borehole is thinner than that typical for the North Sea. It also lacks the major halite members present farther basinwards (although the Main Röt Halite Member is represented by a collapse breccia). The sedimentary log of the core is shown in enclosure Well B.

1.4 Drill Cuttings

In the Southern North Sea, the only direct lithological information available is from cuttings. These are small (generally less than 5 mm) rock fragments which are brought to the surface in the drilling mud during rotary drilling.

The author has logged the middle Triassic cuttings from eight wells; four in the U.K. Sector, two in the Southern Dutch Sector, and two in the Northwest German area (fig. 2.4). Graphs of lithological percentages against depth are referred to as cuttings logs. They are shown on enclosure Wells G to N. In interpreting these cuttings logs, several factors have to be borne in mind:

1.4.1 Sample Interval

Samples are collected over an interval varying from 5 to 20 feet (1.5 to 6.1 metres) in the wells examined. Hence, even if there is no contamination of the sample (see below), it still represents a mixture of lithologies present over a large interval.

1.4.2 Caving

Drilling mud flowing back to the surface may incorporate with it fragments from the borehole wall along with those from the bottom of the well. Hence the cuttings returned to the surface may contain cavings from higher in the well.

Recognition of such cavings is difficult as both the middle and upper Triassic are dominated by red mudstones, and to recognise these as cavings is generally impossible. Certain lithologies, however, are obvious cavings, e.g. small amounts of light grey calcareous shale, found

in samples from wells 42/28-2, 48/6-2 and 49/12-1 (encl. Wells G, H and I), are atypical of the middle Triassic and almost certainly represent cavings from the Rhaetic or Liassic. Usually caving in the middle Triassic is best recognised by comparing the cutting log with the petrophysical logs. For example, in well 48/6-2 (encl. Well H), the Main Röt Halite and Muschelkalk Halite Members have suffered caving. The base of the Main Röt Halite Member is clearly defined on the gamma-ray and sonic logs, yet halite is found in the cuttings samples up to 15 metres below this. Similarly, the samples at the top of the Member have been contaminated with mudstone cavings from the unit above. Note, however, that the harder dolomite at the base of the Muschelkalk Dolomitic Member in this well has not greatly caved into the samples below.

1.4.3 Halite Dissolution

Unless the well is drilled with an oil-based or salt-saturated mud, halite samples will be dissolved away before reaching the surface. In both wells 48/6-2 and 42/28-2 (encl. Wells H and G) the Main Röt Halite Member is clearly identified on the petrophysical logs, yet in the latter well no halite was recovered from the cuttings due to later dissolution.

1.5 Interpretation of Petrophysical and Cuttings Logs

When the above features are borne in mind, it is possible to combine the petrophysical and cuttings logs of a well to produce an interpreted lithology log (see encl. Wells G to N). The cuttings place lithological constraints on the interpretation of the petrophysical responses. It is then possible to predict, from the petrophysical logs

alone, the lithological succession in those wells whose cuttings have not been examined.

2. OUTCROP

In the study area, the middle Triassic is only exposed at outcrop in the Lower Saxony area of north Germany and on the East Midlands Shelf, around and to the north of Nottingham. The latter area is of particular interest, as the correlation of the outcrop succession with that of the basin centre is at best approximate. Outcrop studies have been undertaken in this area, and are discussed in Chapter 4.

In the Lower Saxony area, the author has visited a limited number of middle Triassic outcrops. This sequence has however been studied in detail by many authors, particularly Duchrow (1968), Hinze (1967), Richter-Bernberg (1974) and Schröder (1982) (including a detailed correlation into the subsurface by Geiger and Hopping (1968), NAM/RGD (1980), Philipp (1960) and Trusheim (1961)), and it is beyond the scope of this thesis to add further to this discussion.

CHAPTER 3

CHAPTER 3

MIDDLE TRIASSIC LITHOSTRATIGRAPHY OF THE U.K. SOUTHERN NORTH SEA AND SUBSURFACE EASTERN ENGLAND

1. INTRODUCTION

1.1 Previous Workers

Prior to 1974, no formal subdivision of the offshore Triassic of the North Sea existed, although the lithostratigraphic units of the type area of Lower Saxony (north Germany) had been correlated into the subsurface under the North German Plain (Trusheim 1963), and thence their lateral equivalents had been recognised palynologically in one well in the U.K. Southern North Sea (Geiger and Hopping 1968).

In 1974, the report of the 'Joint Oil Industry - Institute of Geological Sciences Committee on North Sea Nomenclature' (Rhys 1974) proposed subdivision of the Triassic of the Southern North Sea below the Rhaetic (Winterton Formation), into two Groups, the lower Bacton Group, and the upper Haisborough Group. This subdivision differs fundamentally from the tripartite subdivision in the type area of north Germany, where the clastics of the Buntsandstein give way upwards to the carbonates of the Muschelkalk and then back to the clastics of the Keuper. In the U.K. Southern North Sea area, the boundary between the two Groups is placed at a major change from a generally coarse clastic sequence below to a generally argillaceous, evaporitic sequence above. As a result, the evaporitic Röt succession is placed in the upper, Haisborough Group, whereas in north Germany it forms the upper part of the Buntsandstein (Richter-Bernberg 1974).

The Bacton Group is divided into a lower, Bunter Shale Formation and an upper, Bunter Sandstone Formation (Rhys 1974). The upper, Haisborough Group is divided into three Formations, based on the relative proportions of dolomite, halite and anhydrite in the generally argillaceous sequence, and named, in ascending order, the Dowsing Dolomitic Formation, the Dudgeon Saliferous Formation and the Triton Anhydritic Formation (fig. 1.4). This chapter is concerned with the lithostratigraphy of the Dowsing Dolomitic Formation, whose deposits equate with the middle Triassic transgressive phase (Bertelsen 1980).

The Dowsing Dolomitic Formation equates (lithostratigraphically) with the Röt and Muschelkalk Formations of north Germany. However, it was the majority view of the Committee on North Sea Nomenclature (Rhys *op. cit.*), that these Formations could not be separated in the U.K. Sector (except locally in the basin centre), and should hence be combined as the Dowsing Dolomitic Formation. Subdivision of this Formation was then restricted to the recognition of two halitic Members, the Röt and Muschelkalk Halite Members, with a further unit, the Basal Röt Clay (of informal status) added by Brennand (1975).

Since Brennand's paper (*op. cit.*), no further work has been published on the lithostratigraphy of the Triassic of the U.K. Southern North Sea. A new Triassic lithostratigraphic nomenclature has, however, been proposed for the onshore and offshore Netherlands (NAM/RGD 1980) and for the Danish area (Bertelsen 1980). The correlation of the Dutch nomenclature with that of Rhys (1974) is shown in fig. 1.4. A new Triassic lithostratigraphy for the outcrops of eastern England has also been proposed by Warrington *et al.* (1980). The major subdivision of the latter into a lower, Sherwood Sandstone Group and an upper Mercia Mudstone Group coincides with the Bacton/Haisborough Group subdivision

offshore.

1.2 Reasons for a Lithostratigraphic Revision

In the eleven years since Brennand's paper on the Triassic of the North Sea (*op. cit.* 1975), a considerable amount of well-log data has become available in both the U.K. and Dutch Sectors, allowing a much more detailed correlation across this part of the basin. This has enabled the present author to extend the detailed lithostratigraphic subdivision of the Dutch Röt and Muschelkalk Formations (NAM/RGD 1980), across the median-line into the Anglo-Dutch Basin of the U.K. Sector. Indeed, as this subdivision can also be extended across the East Midlands Shelf almost to outcrop, it is felt appropriate that this should form the basis of a new detailed lithostratigraphic subdivision of the Dowsing Dolomitic Formation in the U.K. Southern North Sea. It is also proposed here that the Dowsing Dolomitic Formation (and its proposed Members) be included as a subdivision of the Mercia Mudstone Group in the subsurface of eastern England. The correlation between this subsurface lithostratigraphy and that proposed at outcrop (Warrington *et al.* 1980) is discussed in Chapter 4.

For brevity, the term U.K. Southern North Sea area is used in this thesis to refer to the U.K. Southern North Sea and subsurface eastern England.

1.3 Dowsing Dolomitic Formation Boundaries

The base of the Formation offshore lies at the top of the Bacton Group Bunter Sandstone Formation (Rhys 1974) and at the top of the

Sherwood Sandstone Group in the subsurface of eastern England. In Chapter 6, this boundary is shown to equate with the Hardegsen unconformity which, in the Dutch and north German areas, lies at the base of the Middle Buntsandstein Solling Folge (Trusheim 1963). In this thesis, the sequence boundary which is defined by the unconformity surface is everywhere proposed as the base of the Dowsing Dolomitic Formation. This is significant because it will be shown that the lithostratigraphic equivalents of the Solling Folge locally extend into the U.K. Sector. Hence these deposits are also included within the Dowsing Dolomitic Formation.

The upper boundary of the Dowsing Dolomitic Formation separates a generally dolomitic mudstone succession below from a less dolomitic, locally halitic mudstone succession above (the Dudgeon Saliferous Formation). The boundary, as will be shown in section 19.6.2, equates lithostratigraphically with the Muschelkalk/Keuper boundary of north Germany.

2. NOMENCLATURE

2.1 Formations - the Röt and Muschelkalk v. the Dowsing Dolomitic

In the Dutch nomenclature, the Röt and Muschelkalk are given Formation status, whereas in the U.K. Sector, they are presently combined as the Dowsing Dolomitic Formation (fig. 1.4). Despite assertions to the contrary (Rhys 1974), the boundary between the Röt and Muschelkalk is clearly recognisable throughout the U.K. Sector (it is only difficult to identify in the lower part of Quadrant 53). Hence the question arises: Should these units also be given Formation status in the U.K. Sector?

Attributing Formation status to the Röt and Muschelkalk would require that the term Dowsing Dolomitic Formation be either discarded or redefined (i.e. given Group status). Both are rejected, firstly because the Dowsing Dolomitic Formation is a widely accepted and increasingly used term within the U.K. North Sea oil industry, and has also been included in the nomenclature of other areas (Bertelsen 1980). Secondly, a change of hierarchy (Dowsing Dolomitic Group) would require a similar redefinition of the Dudgeon Saliferous Formation, the Triton Anhydritic Formation and the Haisborough Group, which is beyond the scope of this thesis. Neither is it possible to give Member status to the Röt and Muschelkalk within the Dowsing Dolomitic Formation, as these Members would then contain the two Halite Members already defined by Rhys (*op. cit.*), plus the new Members proposed in this Chapter.

The term Dowsing Dolomitic Formation is hence retained, and it is reluctantly accepted that no formal definition of the Röt and Muschelkalk at Formation or any other level is possible in the U.K. Sector. This problem is, however, partly resolved by the way in which the newly proposed Members are named (see below).

2.2 Naming of Members

As noted in section 1.2, almost all the Members of the Dutch Röt and Muschelkalk Formations can be traced into the U.K. Southern North Sea area. Not only do these units lie between the same boundaries (and are hence true lithostratigraphic equivalents), they are usually of very similar lithology, and are hence in fact continuations of the same lithostratigraphic Member. For this reason, it is here proposed that the names of the Dutch Members (NAM/RGD 1980) be extended into the U.K. Sector,

even though these names are in part contrary to the recommendations of the British and International guides on lithostratigraphic nomenclature (Holland *et al.* 1978 and Hedberg 1976 respectively). They also differ from the usual practice of naming units within the U.K. Southern North Sea after coastal features, shoals or lights (Rhys 1974).

The deviations from the recommended practice are; (a) the use of the terms Lower, Middle and Upper in a formal, rather than an informal sense (e.g. Upper Röt Evaporite Member); (b) the use of the names Röt and Muschelkalk, rather than geographic names, and; (c) the use of each of these names for more than one Member within the Dowsing Dolomitic Formation.

There is a precedent for using the terms Röt and Muschelkalk in the U.K. Southern North Sea: The Members defined by Rhys (1974) were called the Röt and Muschelkalk Halite Members on the basis that "retention of these names would aid familiarisation with the nomenclature proposed for the larger units" (*op. cit.* p.5). In the absence of a formal subdivision of the middle Triassic into the Röt and Muschelkalk Formations, retaining these terms for the individual Members clarifies their position with respect to the Dutch and Germanic litho-stratigraphies.

Slight changes have been made to the Dutch nomenclature, as extended into the U.K. Southern North Sea. Firstly, the term Mudstone replaces Claystone (e.g. Upper Röt Mudstone Member = Upper Röt Claystone Member), as it is felt that 'Claystone' should be restricted to an almost pure clay-grade rock rather than the commonly silty, dolomitic mudstones of the Dowsing Dolomitic Formation; and secondly, in keeping with the Members proposed by Rhys (1974), the term Halite replaces Salt (e.g. Muschelkalk Halite Member = Muschelkalk Salt Member).

2.3 Introduction to the Proposed Members

The proposed lithostratigraphic subdivision of the Dowsing Dolomitic Formation in the U.K. Southern North Sea area (and its relationship to the Dutch Nomenclature) is shown in fig. 3.1.

The Solling Mudstone Member occurs locally in the U.K. Sector, where it is overlain by the Riff Sandstone Member and the Lower Röt Mudstone Member (the latter being the Basal Röt Clay of Brennand (1975)). The Lower Röt Mudstone Member is also present directly overlying the Bunter Sandstone Formation in those areas where the Solling Mudstone Member is absent. The Dutch Main Röt Evaporite Member is subdivided into a halite Member (the Main Röt Halite Member) and a (dolomitic/anhydritic) evaporite Member (the Main Röt Evaporite Member). The Dutch Upper Röt Evaporite Member is likewise subdivided. The Main Röt Halite Member equates with the Röt Halite Member of Rhys (1974). The Intermediate and Upper Röt Mudstone Members are extended into the U.K. Sector in those areas where they are separated by the intervening Upper Röt Halite Member or Upper Röt Evaporite Member. Where such a subdivision is not possible, they are combined as the Main Röt Mudstone Member.

In the U.K. Sector, the Dutch Lower Muschelkalk Member is renamed the Muschelkalk Dolomitic Member, as the lithologies are interbedded dolomites and dolomitic mudstones rather than the thinly bedded, marly limestones typical of the Lower Muschelkalk in the type area of north Germany. The Muschelkalk Salt Member of the Dutch area is renamed the Muschelkalk Halite Member (as proposed by Rhys 1974). A non-halitic, evaporitic unit, the Muschelkalk Evaporite Member can be distinguished, overlying and laterally equivalent to the Muschelkalk Halite Member. In the U.K. Sector (as in parts of the Dutch area) it is

not practical to separate the Middle Muschelkalk Marl Member from the Upper Muschelkalk Member and hence these units (above the Muschelkalk Evaporite Member) are combined as the Muschelkalk Mudstone Member.

3. TYPE AND REFERENCE WELLS

Type and reference wells are proposed for the Dowsing Dolomitic Formation and its Members in the same manner as type and reference sections at outcrop. The type well exhibits a typical development of the unit, while a reference well shows the lateral similarity (or variability) in a different part of the basin.

Ideally, the type well for the Dowsing Dolomitic Formation should have a full suite of petrophysical logs plus core. This criterion is met only by the 'Staithes-20' well (encl. Well B). However, this well is not chosen because the Dowsing Dolomitic Formation is considerably thinner than is typical for the Southern North Sea area (encl. Map 1), and because the Röt and Muschelkalk Halite Members are not present. The well does, however, serve as a reference well for the proposed Dowsing Dolomitic Formation of the Mercia Mudstone Group in the subsurface of eastern England.

The type well proposed for the Dowsing Dolomitic Formation is well 48/12-1 (encl. Well A). This is different from well 49/21-2, the Triassic type well proposed by Rhys (1974), for the reasons outlined below. The reader is once again referred to fig. 2.1 in order to locate the wells mentioned in the text.

3.1 Triassic Type Well 49/21-2

Rhys (1974) in proposing well 49/21-2 as the type well for the Triassic noted the possible presence of a fault at the base of the Muschelkalk Halite Member (fig. 3.2). This fault is of considerable importance to the Dowsing Dolomitic Formation lithostratigraphy because, apart from removing the lower part of the Muschelkalk Halite Member, it also cuts out most of the Muschelkalk Dolomitic Member. The absence of the latter may explain the assertion (*ibid.*) that the Röt and Muschelkalk Formations are inseparable in the U.K. Southern North Sea area. A detailed bed-by-bed correlation between this and two adjoining wells (wells 49/16-1 and 49/21-3) shows that about 58 metres of section are missing from the type well (Rhys (1974) estimates 50 metres missing), and that there is a further fault within the Muschelkalk Mudstone Member, with about 20 metres of section missing (fig. 3.3). For these reasons, this well is considered inappropriate as the type well for the Dowsing Dolomitic Formation.

3.2 Dowsing Dolomitic Formation Type Well 48/12-1 (encl. Well A)

Within the Dowsing Dolomitic Formation this well has many advantages over the Triassic type well 49/21-2. Firstly, the well is apparently unfaulted, and the Muschelkalk Dolomitic Member is clearly developed. Secondly, it is situated in the centre of the U.K. Sector Dowsing Dolomitic Formation basin (encl. Map 1), close to, but not within the abnormally thick deposits of the Sole Pit Trough (which lies to the north-east). The well has a Dowsing Dolomitic Formation thickness of 351 metres, compared with about 325 metres in the area of the Triassic type

well 49/21-2 (and 241 metres within the faulted well itself).

The Upper Röt Evaporite Member is present in the well, whereas well 49/21-2 lies too far from the basin centre for this Member to be developed (encl. Map 12). Finally, a full suite of petrophysical logs are available for the well (unlike well 49/21-2), allowing petrophysical lithology determination in the absence of core. Cuttings have also been logged for an adjoining well (48/6-2, encl. Well H) which is of very similar thickness (347 metres), hence allowing confirmation of lithological interpretations.

Where possible, this well serves as the type well for the individual Members of the Dowsing Dolomitic Formation. However, the Solling Mudstone Member, the Riff Sandstone Member and the Upper Röt Halite Member are absent from the well (and from the Triassic type well 49/21-2), and hence an alternative type well (well 43/20-1) is proposed for these Members. No single well contains all the proposed Members.

3.3 Dowsing Dolomitic Formation Reference Well - 'Staithes-20' (encl. Well B)

Apart from having a full suite of petrophysical logs and being completely cored through the Dowsing Dolomitic Formation, this well compliments the type well in several ways:

48/12-1 type well	Staithes-20 reference well
Typical basin centre succession (351 metres thick)	Typical more marginal succession (154 metres thick)

Typical for Anglo-Dutch Basin	Typical for East Midlands Shelf
Type section for the Dowsing Dolomitic Formation of the Haisborough Group (U.K. Southern North Sea)	Reference section for the Dowsing Dolomitic Formation of the Mercia Mudstone Group (subsurface eastern England)

A comparison between the two wells is shown in fig. 3.4. Alternative and additional reference wells are chosen as and when necessary.

3.4 Type and Reference Wells - Details

In keeping with convention (Hedberg 1976), the co-ordinates of the type and reference wells, along with the logs used, are listed below.

WELL	CO-ORDINATES	LOGS USED	ENCL/FIG
42/28-2	54°04'43"N 0°27'18"E	Gamma-ray Sonic Cuttings	encl. Well G
43/ 8-2	54°45'11"N 1°33'08"E	Gamma-ray Sonic	fig. 3.7
43/17-1	54°20'12"N 1°13'25"E	Gamma-ray Sonic FDC	fig. 3.17
43/20-1	*54°29'44"N 1°56'58"E*	*Gamma-ray Sonic*	fig. 3.6
48/12-1	*53°34'24"N 1°18'30"E*	*Gamma-ray Sonic FDC SNP*	encl. Well A
49/26-4	*53°07'52"N 2°04'57"E*	*Gamma-ray Sonic*	fig. 3.15
Locton-7	Nat.Grid SE9106 8959	Gamma-ray Sonic	fig. 3.11
Staithes-20	Nat.Grid NZ4761 5181	Gamma-ray Sonic FDC SNP Core	encl.Well B
Welton-1	Nat.Grid TF0361 7680	Gamma-ray Sonic	fig. 3.12

Type wells are shown in *Italics*

4. DETAILED LITHOSTRATIGRAPHY - LAYOUT

The individual Members of the Dowsing Dolomitic Formation are described in detail in sections 6 to 19. The upper part of the Bunter Sandstone Formation is described briefly in section 5. The Members are discussed under the following headings: Type well; Reference wells; Definition; Remarks; Log profiles and lithologies; Boundaries; Thickness and lateral distribution; Subdivision; Correlation. This layout is similar to those used for other subsurface lithostratigraphic nomenclatures (e.g. Bertelsen 1980, Deegan and Scull 1977, NAM/RGD 1980). The relationship between lithostratigraphy and biostratigraphy is discussed in section 20.

Thicknesses are quoted in metres throughout. Depths are quoted as on the original logs, i.e. usually in feet below the Kelly Bushing (about 100' above sea-level) in the U.K. Sector. This allows direct reference back to the original logs if so required.

5. BUNTER SANDSTONE FORMATION - Uppermost Part

In order to determine accurately the base of the Dowsing Dolomitic Formation, it is necessary to discuss briefly the development of the uppermost Bunter Sandstone Formation. The type well for the Formation is 49/21-2 (fig. 3.2), proposed by Rhys (1974). The development in this well is typical for the majority of the U.K. Southern North Sea area, however, well 44/23-1 (fig. 3.5) shows a previously unreported, more argillaceous development typical of the Quadrant 44 area.

Over the majority of the U.K. Sector, the Formation comprises a series of thick sandstones interbedded with thin shales (Rhys 1974). In

this area, the contact with the Dowsing Dolomitic Formation is clearly marked by a sudden upwards increase in gamma-ray values. This is most pronounced where the Formation is overlain by the Lower Röt Mudstone Member (e.g. 48/12-1, encl. Well A), but it is also distinctive where higher Members of the Dowsing Dolomitic Formation directly overlie the Bunter Sandstone Formation (e.g. well 53/12-3, encl. Well F). The contact is equally clearly recognised on the FDC/SNP overlays (encl. Wells A to F), where there is a marked change from a positive separation below to a negative separation above. Only in the most marginal areas is the contact blurred by a more sandy base to the Dowsing Dolomitic Formation (e.g. well 53/12-3, encl. Well F).

The approximate position of the boundary is seen on the cuttings logs by an upward decrease in the sandstone fraction from about 30% to 0%-5% (encl. Wells G to J). The contact is blurred by mudstone cavings which are indistinguishable from the in situ mudstones of the Bunter Sandstone Formation. In the cored 'Staithes-20' well (encl. Well B), the uppermost 3.4 metres of the Formation comprises fine to medium-grained, well-sorted sandstones, occasionally with thin red-brown mudstone layers (up to 4 cm thick) and clasts (up to 2 cm). The exact position of the contact is not immediately obvious in the core (although there is a clear overall distinction between the mudstones above and the sandstones below). Based on the petrophysical logs, the contact lies at the base of a sandstone containing angular red-brown mudstone clasts ranging up to 5 cm in diameter. These clasts are considerably larger than those in the sandstones below.

In Quadrant 44 (and possibly part of Quadrant 43), the Bunter Sandstone Formation shows a more argillaceous development (indicated by higher gamma-ray values). In general, the top of the Formation can still

be recognised by the increase in gamma-ray values into the overlying Solling Mudstone Member (e.g. fig. 3.5), but in those areas where the Formation is particularly argillaceous, the upper boundary is very difficult to determine. No cuttings were logged for wells in this area.

It is not possible on the data available, to determine the lateral extent of this more argillaceous Bunter Sandstone Formation, but it appears to coincide with the area where the overlying Solling Mudstone Member is present (encl. Map 2). This is seen on fig. 3.5, with clean (low gamma-ray) sands in well 44/21-1 (outside the area of Solling Mudstone Member deposition), and more argillaceous (higher, serrated gamma-ray) sands in wells 44/23-1 and 44/24-1 (within the area of Solling Mudstone Member deposition). This argillaceous development is probably an extension of that in the Dutch Sector, where the equivalents of the individual Middle Buntsandstein sandstone/shale cycles (Folgen) of north Germany have been recognised. Hence these Folgen may extend locally into the U.K. Sector.

The lithostratigraphic correlation of this Formation across the Germanic Basin is shown on the correlation panel of encl. Map 1.

6. SOLLING MUDSTONE MEMBER - (Dowsing Dolomitic Formation - New Member)

6.1 Type Well 43/20-1 (fig. 3.6)

Depths: 5280' - 5315'

Thickness: 10.7 metres

6.2 Reference Well

None Proposed

6.3 Definition

A mudstone unit occurring locally at the base of the Dowsing Dolomitic Formation, and separated from the overlying and regionally extensive Lower Röt Mudstone Member by the Riff Sandstone Member.

6.4 Remarks

The lithostratigraphic equivalent of the Solling Folge of north Germany has not previously been identified in the U.K. Southern North Sea area. However, by detailed correlation, the equivalents of the Dutch Solling Claystone Member (NAM/RGD 1980) can be seen to extend into the U.K. Southern North Sea area, where they equate with two mudstone sequences separated by a thin sandstone. Profiles in the Quadrants 43 and 44 area (figs. 3.5 and 3.7) show this close similarity with the development in the Dutch Sector (fig. 3.8). The lower of the two mudstones is only locally present in the U.K. Sector, while the upper mudstone forms the regionally extensive Basal Röt Clay of Brennand (1975). It is the lower mudstone (which forms the majority of the Dutch Solling Claystone Member) which is, in the U.K. Sector, referred to as the Solling Mudstone Member. The higher mudstone is named the Lower Röt Mudstone Member, and the intervening sandstone is called the Riff Sandstone Member.

The Solling Mudstone Member is not present in either the Dowsing Dolomitic Formation type well 48/12-1, or in the Triassic type well 49/21-2. It is also absent from the proposed Dowsing Dolomitic Formation of the Mercia Mudstone Group of eastern England.

6.5 Log Profiles and Lithologies

The Member shows generally high gamma-ray and sonic values, indicative of a mudstone. The slightly serrated nature of the gamma-ray log, as in type well 43/20-1 (fig. 3.6), may indicate the presence of thin interbedded sandy or silty horizons. No FDC/SNP overlay is available for the wells which penetrated the Member.

The Member does not occur in any of the U.K. wells whose cuttings were logged. Further east, the cuttings logs of the Dutch well Q/4-1 and German wells 'Ems River Mouth' and 'South Bremen' indicate the Solling Mudstone Member equivalent to be a red-brown, silty mudstone, locally containing up to 10% sandstone and possibly anhydrite (encl. Wells L, M and N). A similar lithological development is suggested for the U.K. Sector.

6.6 Boundaries

6.6.1 Lower

The Solling Mudstone Member is present in the area where the underlying Bunter Sandstone Formation shows an argillaceous development. This contact is discussed in section 5 .

6.6.2 Upper

The upper boundary is marked by a sudden decrease in gamma-ray log values into the overlying Riff Sandstone Member (e.g. type well, fig. 3.6). This boundary is clearest where the Riff Sandstone Member is well developed. Towards the north-east, where the latter Member thins and becomes increasingly difficult to recognise, the boundary separating the

Solling Mudstone Member from the Lower Röt Mudstone Member is difficult to place (it is, however, usually recognisable in the U.K. Sector).

6.7 Thickness and Lateral Distribution (encl. Map 2)

The Member is absent over the majority of the U.K. Southern North Sea area, occurring only in the north-eastern part. It thickens fairly consistently towards the north-east from a margin running north-west/south-east from (possibly) the upper part of Quadrant 42, through the upper part of Quadrant 43, and into the lower part of Quadrant 44. The maximum thickness in the U.K. Sector is about 22 metres (well 44/2-1).

In the Southern Dutch Sector, a similar trending margin, with similar thickening towards the north-east is seen. This margin closely follows the south-western limit of the Broad Fourteens Basin. The margin of the Member in the U.K. Sector may hence reflect an extension of this Basin into the north-eastern part of the U.K. Southern North Sea (see Chapter 5). This latter area is hence referred to as the U.K. Broad Fourteens Basin.

The Member is absent due to erosion over the Cleaver Bank and Mid-North Sea Highs, but the isopachs do not indicate any thinning towards either of these structures.

6.8 Subdivision

The Member is not subdivided.

6.9 Correlation (encl. Map 2)

The Solling Mudstone Member equates with the majority of the Solling Claystone Member of NAM/RGD (1980) in the Dutch area, although the latter also includes the equivalents of the Lower Röt Mudstone Member. In like manner, the Member is considered to equate with the majority of the Solling Ton of Richter-Bernberg (1974) in north Germany (e.g. encl. Wells M and N). In East Germany, it similarly equates with the Tonige Zwischenschichten (overlying the Solling Basissandstein) of Dockter *et al.* (1980).

The Member has no equivalent at outcrop in eastern England, and based on the reported lithologies, it may also be absent in the Danish and Polish areas (Bertelsen 1980 and Tokarski 1965 respectively). This is discussed further in Chapter 6.

7. RIFF SANDSTONE MEMBER (Dowsing Dolomitic Formation - New Member)

7.1 Type Well	43/20-1	(fig. 3.6)	
		Depths:	5266' - 5280'
		Thickness:	4.3 metres
7.2 Reference Well	43/8-2	(fig. 3.7)	
		Depths:	6138' - 6159'
		Thickness:	6.4 metres

7.3 Definition

A thin sandstone unit separating the locally developed Solling

Mudstone Member below from the overlying regionally extensive Lower Röt Mudstone Member.

7.4 Remarks

As this Member may be related to either the underlying Solling, or the overlying Röt succession (see Chapter 6 section 4), a new non-generic name, the Riff Sandstone Member, is proposed (as opposed to the Upper Solling Sandstone or Lower Röt Sandstone). The name is derived from the North West Riff, a sea-bed topographic feature in Blocks 43/8 and 43/13, in the area where the Member is clearly developed (Admiralty Chart No. 266; lat. 1°15' East; long. 54°40' North).

The Member is not present in the Dowsing Dolomitic Formation type well 48/12-1, or in the Triassic type well 49/21-2. It is also absent from the proposed Dowsing Dolomitic Formation of the Mercia Mudstone Group of eastern England.

7.5 Log Profiles and Lithologies

In its type well 43/20-1 (fig. 3.6), the Riff Sandstone Member shows a low gamma-ray response, similar to those produced by the thin sandstones of the (Dutch) Main Buntsandstein Formation (e.g well L/2-1, fig. 3.8). Hence, the Member is likewise inferred to be a generally clean sandstone. Direct confirmation of this is not possible, as FDC/SNP overlays are not available for those wells in which the Member is present, and the Member is not present in the cored 'Staithes-20' well, or in any of the U.K. Sector wells whose cuttings were logged.

Indirect confirmation of the sandstone lithology comes from the

sonic log of the type well (fig. 3.6). The underlying Bunter Sandstone Formation shows an abnormally high Δt response due to the presence of gas (this is the Gordon field of the Esmond gas complex (Bifani 1986)), and at the very top of the Formation, a low Δt peak presumably reflects a zone of (anhydrite?) cementation. An identical sequence (gas effect overlain by cementation effect) is seen in the thin Riff Sandstone Member, confirming the similar lithology.

In reference well 43/8-2 (fig. 3.7), a different log profile is encountered. The gamma-ray and sonic peaks are less distinct, and of a more serrated nature. The Member is here interpreted as a more argillaceous sandstone with interbedded mudstone.

7.6 Boundaries

In the type well (fig. 3.6), there is a marked decrease in the gamma-ray values into the Riff Sandstone Member from the Solling Mudstone Member below, and a marked increase in both gamma-ray and sonic log values into the Lower Röt Mudstone Member above. Towards the north-east, the boundaries become less distinctive (fig. 3.7).

In well 43/11-1 (fig. 3.7), the Member is a relatively clean sandstone similar to the type well, and hence has a distinctive upper boundary with the overlying Lower Röt Mudstone Member. However, the lower boundary is not so clear because the Solling Mudstone Member is very thin, making it difficult to separate the Riff Sandstone Member from the underlying Bunter Sandstone Formation. In this well, the blocky Riff Sandstone Member profile can be distinguished from the more serrated profile of the underlying Bunter Sandstone Formation, but this is not always the case. In wells where the Solling Mudstone Member is absent

(e.g. well 42/14-1, fig. 3.7) the Riff Sandstone Member, if present at all, is indistinguishable from the Bunter Sandstone Formation.

7.7 Thickness and Lateral Distribution (encl. Map 3)

The Riff Sandstone Member and its equivalents are only present locally in the U.K. and Dutch Sectors of the Southern North Sea. It occurs in a belt running north-west/south-east from Quadrant 43 (and possibly Quadrant 42) through Quadrant 44 and into Dutch Quadrants K, L, P and Q (and locally onshore in the area south of the Texel-Ijsselmeer High). The Member is absent due to erosion over the Cleaver Bank High, the Mid-North Sea High and the Texel-Ijsselmeer High, but shows no evidence of a margin against these structures.

The south-western margin of the Member appears to coincide with the margin of the underlying Solling Mudstone Member and is hence restricted to the Broad Fourteens Basin. The Member may extend farther south-west into the Anglo-Dutch Basin, but it is thin and indistinguishable from the underlying Bunter Sandstone Formation. The north-eastern limit is equally difficult to define as the Member becomes increasingly argillaceous (in the U.K. Sector) until it passes laterally (in Dutch Quadrants L and F) into the Solling Claystone Member (fig. 3.8).

The thickness of the Riff Sandstone Member varies from 1-2 metres where it is tentatively recognised towards its margins, to about 6 metres. As a single massive sandstone it thickens slightly from its south-western margin to about 4 metres in the type well 43/20-1. It then continues to thicken towards the north-east, due to an increasing number of thin interbedded mudstones. Eventually, the individual sandstone

stringers pass laterally into the Solling Mudstone Member, and hence the Riff Sandstone Member thins and becomes difficult to recognise (fig. 3.7).

7.8 Subdivision

The Member is not subdivided.

7.9 Correlation (encl. Map 4)

The equivalent of the Riff Sandstone Member, locally occurs in the upper part of the Dutch Solling Claystone Member of NAM/RGD (1980). Over the remainder of the Dutch area, and in north Germany, no equivalent sandstone is present. In East Germany, the locally developed Thuringer Chirotheriensandstein of Dockter *et al.* (1980) occurs at a similar horizon.

8. LOWER RöT MUDSTONE MEMBER (Dowsing Dolomitic Formation - New Member)

8.1 Type Well	48/12-1	(encl. Well A)
		Depths: 4856' - 4885'
		Thickness: 8.8 metres
8.2 Reference Wells	Staithes-20	(encl. Well B)
		Depths: 2069' - 2088'
		Thickness: 5.8 metres

42/28-2 (encl. Well G)

Depths: 6177' - 6209'

Thickness: 9.8 metres

8.3 Definition

A generally thin (about 8 metres thick), regionally extensive mudstone, forming the lowest Member of the Dowsing Dolomitic Formation over most of the U.K. Southern North Sea area. In Quadrant 44, it is separated from the underlying, locally developed Solling Mudstone Member by the thin Riff Sandstone Member.

8.4 Remarks

This Member is the informally defined Basal Röt Clay of Brennand (1975). This name is not adopted here, because this unit is only the basal Member of the Dowsing Dolomitic Formation in those areas where the Solling Mudstone and Riff Sandstone Members are absent. The name proposed here, the Lower Röt Mudstone Member, is not adopted from the Dutch nomenclature, where the equivalent unit forms the upper part of the Solling Claystone Member. The name proposed however, is in keeping with the Intermediate and Upper Röt Mudstone Members higher in the Dowsing Dolomitic Formation, whose names are extended from the Dutch nomenclature.

The Member is present in both the U.K. Southern North Sea Dowsing Dolomitic Formation, and in the newly proposed Dowsing Dolomitic Formation of the Mercia Mudstone Group in the subsurface of eastern England.

8.5 Log Profiles and Lithologies

Throughout the U.K. Southern North Sea area, the Member shows distinctive high gamma-ray values, indicative of a mudstone (e.g. type well 48/12-1, encl. Well A). These are frequently matched by high sonic values. The result is a distinctive log profile, occurring between the Bunter Sandstone Formation and the Main Röt Halite Member, which provides a regional marker horizon recognisable over most of the U.K. Southern North Sea area. The slightly serrated sonic response (as in the type well) is indicative of more silty or dolomitic mudstone interbeds. The large negative separation on the FDC/SNP overlay in the type well, and in the reference well 'Staithes-20' (encl. Well B), confirm the dominant mudstone lithology.

In well 48/6-2 (encl. Well H), close to the type well, the cuttings are dominated by halite cavings, with the red-brown mudstone cuttings representing the in situ lithology. In well 49/12-1 (encl. Well I), 5-10% sandstone and green-grey mudstone probably represent interbeds within the red-brown mudstone. In the cored 'Staithes-20' well (encl. Well B), red-brown, medium to fine-grained sandstones occur at the base of the Member. These contain red-brown mudstone clasts (up to 5 cm) and disrupted mudstone laminae (Plate 3.1). The basal sandstones give way abruptly to a generally unlaminated red-brown silty mudstone which dominates the Member. Occasional thin green silty dolomitic horizons are also present (Plate 3.2).

In detail, two slightly different gamma-ray profiles can be recognised in areas where the Member is over 6 metres thick. The first is generally symmetrical around the mid-point of the Member, and may be described as a serrated letter 'U' turned on its side. The type well

(encl. Well A) and well 49/12-1 (encl. Well I) are examples of this. The second profile shows an asymmetrical 'serrated funnel' profile, with gamma-ray values generally decreasing upwards. This is clearly seen in reference well 42/28-2 (encl. Well G). The two profiles grade laterally one into the other and hence a boundary between them is difficult to determine. Well 48/6-2 (encl. Well H) shows an intermediate profile.

The funnel-shaped gamma-ray profile is mainly developed in the area around the Dowsing Fault Zone, both on the East Midlands Shelf and in the Anglo-Dutch Basin. This profile is not developed farther east, except possibly in the north of Quadrant 43 (fig. 3.9). The possible significance of the different profiles is discussed in Chapter 6.

As the Member thins towards the basin margins, it becomes increasingly difficult to recognise on logs, until eventually, in the south of the Anglo-Dutch Basin, it is overstepped, and the Main Röt Evaporite Member lies directly on the Bunter Sandstone Formation (see Chapter 6).

8.6 Boundaries

8.6.1 Lower

The boundary with the Bunter Sandstone Formation is discussed in section 5, and the boundary with the Riff Sandstone Member is discussed in section 7.6.

8.6.2 Upper

The upper boundary is marked by a sudden decrease in both gamma-ray and sonic values upwards into the Main Röt Halite Member or Main Röt Evaporite Member. This boundary is most distinct where the

Member is overlain by the Main Röt Halite Member (as in the type well 48/12-1), but is still clearly recognised where it is overlain by the Main Röt Evaporite Member (e.g. reference well 'Staithes-20', encl. Well B). The boundary is distinct even where the general profile of the Member is of decreasing upwards gamma-ray values (e.g. well 42/28-2 (encl. Well G)).

Where the Member is overlain by the Main Röt Halite Member, the boundary is marked by a change from a large negative, to a very large positive separation on the FDC/SNP overlay (encl. Well A). Where the Member is overlain by Main Röt Evaporite Member, or where a dolomite/ anhydrite sits at the base of the Main Röt Halite Member, the separation remains negative, but the boundary is marked by a change to very high ρ_b values on the FDC log (e.g. encl. Well B).

From cuttings, the boundary is distinct where halites from the Main Röt Halite Member are preserved in the samples (e.g. well 48/6-2, encl. Well H). The boundary is marked by a decrease in the red-brown mudstone percentage upwards into the Main Röt Halite Member. Halite cavings blur the contact. In wells 42/28-2 and 49/12-1 (encl. Wells G and I), where halite is not preserved in the cuttings, the mudstones of the Lower Röt Mudstone Member are indistinguishable from the cavings in the Main Röt Halite Member samples.

An abrupt colour change marks the boundary in the core of the 'Staithes-20' well (encl. Well B). The red-brown, generally unlaminated mudstones of the Lower Röt Mudstone Member give way abruptly to the green-grey micritic dolomites and interbedded dolomitic mudstones of the lowermost Main Röt Evaporite Member. The contact is easily identified on Plate 3.3.

8.7 Thickness and Lateral Distribution (encl. Map 4)

The Member is present over the majority of the U.K. Southern North Sea area, with the exception of Quadrant 52 and most of Quadrant 53. It thickens northwards into the basin from a margin running east-south-east from the area of the 'Torksey' well in eastern England, to the north of the Norfolk coast and into Block 53/4. The isopachs also indicate the existence of a margin to the west of the present outcrop, presumably against the Pennine High. From the margins, the Member thickens to about 8 metres over the southern part of Quadrants 47, 48 and 49, and is then 8 to 12 metres thick over the majority of the U.K. Sector. The Member thins again towards the north-west, but the isopachs do not show any evidence of a margin against the Mid-North Sea High (or against the Cleaver Bank High). In detail thicknesses vary between the various structural elements within the basin.

8.7.1 The East Midlands Shelf/Anglo-Dutch Basin

The Member shows a similar overall thickness both on the East Midlands Shelf and in the Anglo-Dutch Basin, although the isopachs indicate a much more gradual thickening into the basin from the southern margin in the former area. In the latter area, in the lowermost part of Quadrant 49 and the uppermost part of Quadrant 53, the isopachs are much closer spaced, and the Member thickens from its margin to over 8 metres thick within the space of a single licence block (e.g. Block 49/26). It then thickens only slightly to between 10 and 12 metres over the remainder of the Anglo-Dutch Basin.

8.7.2 Broad Fourteens Basin

The Member is considerably thicker in the proposed U.K. Broad Fourteens Basin than over the remainder of the U.K. Sector. From a minimum thickness of about 9 metres, it thickens to 16.5 metres in well 43/20-1 (fig. 3.6), and has been tentatively identified at 21 to 23 metres thick in wells 44/7-1, 44/14-1 and 44/19-2 (the thickness of all Members below the Main Röt Halite Member in these wells is suspect).

8.8 Subdivision

A rough lateral subdivision is made, based on the gamma-ray profile (see section 8.4). No vertical subdivision is made.

8.9 Correlation (encl. Map 4)

The Member's equivalent has not previously been named outside the U.K. Sector. In the Dutch area, it forms the uppermost part of the Solling Claystone Member of NAM/RGD (1980) (fig. 3.8), and likewise in north Germany it forms the uppermost part of the Solling Ton of Richter-Bernberg (1974). In East Germany it probably equates with the Tonige Grenzschichten (clayey boundary beds) of Dockter *et al.* (1980).

In the Danish area, a thin (about 10 metre thick) mudstone is underlain by sandstones and overlain by the equivalent of the Main Röt Evaporite Member (see Ørslev-1 well from Bertelsen (1980)). This succession is very similar to the succession Bunter Sandstone Formation — Lower Röt Mudstone Member — Main Röt Halite Member seen over most of the U.K. Southern North Sea area, and hence the present author believes that this thin mudstone is the Lower Röt Mudstone Member equivalent. In

the nomenclature of Bertelsen (*op. cit.*), this mudstone is placed at the top of the Danish Bunter Sandstone Formation, rather than at the base of the Danish Dowsing Dolomitic Formation.

In the Polish area, a sequence very similar to that of the U.K. and Danish Sectors is found. Electric (resistivity) log profiles, presented by Tokarski (1965) for the Fore-Sudetic Monocline region of Poland, show a sequence of thick sandstones, separated from the equivalents of the Main Röt Halite/Evaporite Member by a thin (4 to 6 metre thick) mudstone (fig. 3.10). This remarkable similarity with the succession in the U.K. Southern North Sea area (over 1000 kilometres to the west) allows this thin mudstone also to be tentatively correlated with the Lower Röt Mudstone Member. This mudstone is also considered to be the lowermost Member of the Röt (Lower Röt Member) by Fuglewicz (1980). These basinwide correlations of the Lower Röt Mudstone Member are discussed further in Chapter 6 section 5.

At outcrop in eastern England, the Lower Röt Mudstone Member is represented by the basal red mudstones of the Retford Formation of Warrington *et al.* (1980).

9. MAIN RÖT HALITE MEMBER (Dowsing Dolomitic Formation - Renamed Member)

9.1 Type Well	48/12-1	(encl. Well A)
		Depths: 4652' - 4856'
		Thickness: 62.2 metres
9.2 Reference Well	Locton-7	(fig. 3.11)
		Depths: 3332' - 3472'
		Thickness: 42.7 metres

9.3 Definition

A halite sequence lying between the Lower Röt Mudstone Member and the Main Röt Evaporite Member, and characterised by thick halite beds separated by thin mudstone interbeds.

9.4 Remarks

The Main Röt Halite Member lies between the same boundaries as the Röt Halite Member defined by Rhys (1974), shown here on fig. 3.2. The prefix 'Main' is added, as in the Dutch Sector (NAM/RGD 1980), to distinguish this halite from the overlying, thinner, less extensive Upper Röt Halite Member.

The Member is present both in the U.K. Southern North Sea Dowsing Dolomitic Formation, and in the proposed Dowsing Dolomitic Formation of the Mercia Mudstone Group in the subsurface of eastern England. The proposal of Warrington *et al.* (1980), that the Member should be called the Esk Evaporite Formation in the latter area, is rejected as an unnecessary complication of the nomenclature. Also, this name has not been used in the subsequent literature (Robson 1980, Riddler 1981).

The Member is absent from the cored 'Staithes-20' reference well, although its former presence is indicated by a non-halitic collapse breccia (which is here included in the Main Röt Evaporite Member). This collapse breccia is atypical with respect to the nearby boreholes which contain about 100' (31 metres) of halite (Woods 1973). For this reason, encl. Map 5 is contoured as if the Main Röt Halite Member was 31 metres thick in the 'Staithes-20' area. 'Locton-7' is chosen as an alternative reference well for this Member on the East Midlands Shelf and subsurface

eastern England.

9.5 Log Profiles and Lithologies

The Main Röt Halite Member shows distinctive blocky gamma-ray and sonic log profiles, with broad zones of low log values separated by thin zones of high log values (e.g. type well 48/12-1, encl. Well A). The predominance of thick halite beds is seen directly from the sonic log, where the measured Δt value lies close to the predicted Δt_{ma} value for halite of 67 μ.sec/ft. The thin, 2 to 3 metres thick, zones of high gamma-ray and sonic values represent mudstone interbeds. Small variations in Δt within the individual halite beds indicate the presence of thin mudstones, dolomites and anhydrites which are too thin (or impure) to develop their true log responses. This is clearly seen on the sonic log of the type well, where dolomite/anhydrite interbeds show kicks to slightly lower Δt values, while mudstones show deflections to slightly higher values. A similar profile is seen in the Member in the subsurface of eastern England (e.g. reference well 'Locton-7', fig. 3.11). Further evidence of the dominant halite lithology is given by the FDC/SNP overlay of the type well (encl. Well A), which shows a large positive separation with FDC values around 2.04 gm/cc (ρ_{ma} for halite).

Halite is not always preserved in the cuttings of the wells in which the Member is present. Wells 42/28-2 and 49/12-1 (encl. Wells G and I) show evidence of halite on the sonic logs, but not in the cuttings. As a result, the cuttings logs are made up primarily of cavings from above, although some of the cuttings presumably represent the non-halitic interbeds in the Member. In well 48/6-2 (encl. Well H), the dominant lithology is confirmed by halite preserved in the cuttings, where

(allowing for obvious caving) the Member is seen to be composed mainly of milk-white to orange-brown translucent halite, with about 5% dark grey dolomite and white anhydrite. The thin mudstone interbeds in the Member are indistinguishable in the cuttings from the mudstone cavings from above.

9.6 Boundaries

9.6.1 Lower

This is placed at the top of the Lower Röt Mudstone Member as described in section 8.6.2. Hence it may occur at the base of (a) the first halite bed (e.g. type well 48/12-1), or (b) the base of a thin dolomite/anhydrite bed which either directly underlies the first halite, or is separated from it by the first of the thin interbedded mudstones (e.g well 42/28-2, encl. Well G). This non-halitic basal sequence is unusually thick in the latter well (where it is 8.5 metres). Generally it is less than 3 metres thick and is hence included as part of the Main Röt Halite Member, whereas the thicker dolomites and anhydrites immediately overlying the halite are placed separately in the Main Röt Evaporite Member.

9.6.2 Upper

The upper boundary of the Member is placed at the top of the last recognisable halite bed. This contact is usually abrupt and well defined, with a change from the generally blocky gamma-ray/sonic profile of the Main Röt Halite Member, into the serrated profile of the Main Röt Evaporite Member (e.g. reference well 'Locton-7', fig. 3.11). Occasionally, as in the type well (encl. Well A), thin interbedded

halites and mudstones occur at the top of the Member. These also give a serrated gamma-ray and sonic profile, and it is not always possible to distinguish this from the serrated profile of the Main Röt Evaporite Member. In the type well, this problem is resolved by reference to the FDC/SNP overlay, where the thin halites show a distinctive positive separation, while the overlying dolomites, anhydrites and mudstones show a negative separation. Unfortunately the overlay is not normally available. Hence, the general rule-of-thumb used is that if the uppermost halite is dubious, or is thinner than the mudstone separating it from the underlying halites, it is placed in the Main Röt Evaporite Member. Based on this, the uppermost halite in the type well 48/12-1 (encl. Well A) and in 42/28-2 (encl. Well G) is placed at the top of the Main Röt Halite Member, while the possible halites in 48/6-2 (encl. Well H) and 49/12-1 (encl. Well I) are placed in the Main Röt Evaporite Member.

The halites of the Main Röt Halite Member pass laterally, towards the basin margin, into dolomites and anhydrites of the Main Röt Evaporite Member. The upper boundary is hence diachronous (fig. 3.6).

9.7 Thickness and Lateral Distribution (encl. Map 5)

In the U.K. Southern North Sea area, the Member occurs in a discreet basin with a margin to the north against the Mid-North Sea High and to the east against the Cleaver Bank High. A further margin extends from the bottom of Quadrant 41 to the bottom of Quadrant 49. The origin of these margins (depositional v. post-depositional) is considered in Chapter 6.

9.7.1 East Midlands Shelf

The Member is absent over most of the East Midlands Shelf. In Quadrant 47 it occurs in the area towards the Dowsing Fault Zone, but its thickness is generally less than that to the east of the fault. The complex Dowsing Fault Zone (taken from Day *et al.* 1981) is shown somewhat schematically on the enclosed maps, and hence it is possible that the 45 metre-thick halites of wells 47/8-1 and 47/8-2 may actually be on the downthrown side of this fault. The fault is responsible for the Members' absence in wells 47/15-1 and 47/15-2. These wells, surrounded by halite (encl. Map 5), presumably contain collapse breccias due to dissolution associated with the fault zone.

The main development of the Member west of the Dowsing Fault Zone trends east-west through Quadrants 42 and 41, and onshore to the north of Flamborough Head and south of Middlesborough. This area coincides closely with that of the Jurassic Cleveland Basin (Kent 1980), and is considered further in Chapter 5.

In the area around well 41/24-1 there is a considerable thinning of the Member (from +40 metres in reference well 'Locton-7' and in well 47/21-1, to 17 metres in well 41/24-1). This could result from a depositional 'high', as proposed by Riddler (1981), but as the area coincides with the Scarborough Dome inversion (Kent 1980 and BGS map: 'Tyne Tees Sheet, 1:250,000 series'), it is likely that this is a solution feature associated with the post-Triassic inversion of the Cleveland Basin.

9.7.2 Anglo-Dutch Basin/Broad Fourteens Basin

The Member is present over most of the Anglo-Dutch Basin, where it thickens from its margins to a thickness of between 40-70 metres.

Immediately on the downthrown side of the Dowsing Fault Zone, the Sole Pit Trough was active as a more rapidly subsiding area, with the Member up to 109 metres thick (well 47/5-1).

In the Broad Fourteens Basin, the Member shows a similar thickness to that in the Anglo-Dutch Basin (40-70 metres). However wells 43/20-1 and 44/24-1 do show a slightly thicker development (72 and 76 metres respectively), which may indicate a local depo-centre in this area.

9.8 Subdivision

The Main Röt Halite Member can be subdivided vertically into (up to) six units, based on the thin but distinctive mudstone breaks between the halites (e.g. type well 48/12-1, encl. Well A). These units can be correlated not only throughout the U.K. Sector, but throughout the whole study area. In Chapter 6 section 6.1, it will be shown that each mudstone represents the start of a major evaporite cycle, and these units are hence named, from the base up, Cycles 'A' to 'F'. The thickness and lateral distribution of the halites of the first five cycles are shown on encl. Maps 6 to 10 (Cycle 'F' is so rarely halitic that no map is enclosed). Encl. Map 11 shows the 5 metre halite isopach of each of the cycles. The marginal dolomites and anhydrites of each cycle together form the Main Röt Evaporite Member

No lateral subdivision of the Member is made.

9.9 Correlation (encl. Map 5)

The Main Röt Halite Member equates with the majority of the

Dutch Main Röt Evaporite Member of NAM/RGD (1980), and the majority of the Unteres Röt Salinar of Richter-Bernberg (1974) in north Germany. In both areas, the development is very similar to that in the U.K. Sector (e.g. Dutch well Q/4-1, encl. Well L, and German wells 'Ems River Mouth' and 'South Bremen', encl. Wells M and N). In both the Dutch and German nomenclatures, the Members equivalent includes the overlying dolomites and anhydrites, which in the U.K. Sector are here proposed as the Main Röt Evaporite Member.

In East Germany, the Member equates with the Röt Steinsalz (and Basisanhydrit) of Docter *et al.* (1980), while in the Danish area it equates with the Röt Halite Member of Jacobsen (1982). In Poland, the Lower Gypsum Beds of Fuglewicz (1980) are, strictly speaking, the equivalent of the non-halitic Main Röt Evaporite Member. However, they do locally contain halite (up to 13 metres in one well on fig. 3.10) and hence in part equate with the Main Röt Halite Member.

10. MAIN RöT EVAPORITE MEMBER (Dowsing Dolomitic Formation - New Member)

10.1	Type Well	48/12-1	(encl. Well A)
			Depths: 4632' - 4652'
			Thickness: 6.1 metres
10.2	Reference Well	Welton-1	(fig. 3.12)
			Depths: 573 - 583 metres
			Thickness: 10.0 metres

10.3 Definition

A series of anhydrites, dolomites and interbedded dolomitic mudstones immediately overlying the Main Röt Halite Member, Lower Röt Mudstone Member or the Bunter Sandstone Formation, and sitting immediately beneath the Main (or Intermediate) Röt Mudstone Member.

10.4 Remarks

The Main Röt Evaporite Member forms the marginal equivalent of the basinal Main Röt Halite Member. As the uppermost halites of the latter Member are less extensive than those below, marginal dolomites and anhydrites of the Main Röt Evaporite Member overlie the Main Röt Halite Member as well as occurring marginal to it, throughout the U.K. Southern North Sea area. Only in one well, in the Sole Pit Trough, are all the evaporite cycles halitic, and hence the Main Röt Evaporite Member is absent (well 47/5-1).

The Member occurs in both the Dowsing Dolomitic Formation of the U.K. Southern North Sea, and in the proposed Dowsing Dolomitic Formation of the Mercia Mudstone Group of eastern England. 'Welton-1' is chosen as the reference well for the latter area, as the Member in the 'Staithes-20' well is a collapse breccia.

10.5 Log Profiles and Lithologies

The Member shows a serrated gamma-ray and sonic log profile, with log values generally lower than those in the overlying Mudstone Members, both in the basin centre where it overlies the Main Röt Halite

Member (e.g. type well 48/12-1, encl. Well A), and near the margins where the Halite Member is absent (e.g. reference well 'Welton-1', fig. 3.12). The highly serrated sonic log profile is particularly distinctive, and includes very low Δt peaks, approaching 55 μ.sec/ft, indicative of dolomites or anhydrites. Distinguishing between these lithologies is only possible in the few wells for which the FDC log is available (ρ_{ma} of dolomite = 2.87 gm/cc, ρ_{ma} of anhydrite = 2.95 gm/cc). The negative separation on the FDC/SNP overlay supports the interpretation of dolomites/anhydrites with interbedded argillaceous units.

These lithologies are confirmed from the cuttings logs, despite the large amount of mudstone cavings. In well 42/28-2 (encl. Well G), and to a lesser extent in well 49/12-1 (encl. Well I), there is an increase in the percentage of dolomite in the cuttings compared with the Members above and below. Anhydrite is also present. The interbedded mudstones are indistinguishable in the cuttings from the cavings from above.

The Member is atypically developed in the cored 'Staithes-20' well where it is represented in part by a collapse breccia (encl. Well B). Two low gamma-ray and sonic peaks at the base of the Member comprise respectively a green-grey, argillaceous dolomite, overlain by a generally massive, grey anhydrite bed. Overlying this basal zone is the collapse breccia, which comprises highly brecciated zones with dolomite, anhydrite and silty mudstone clasts in a silty mudstone matrix (Plate 3.4), separated by generally less brecciated dolomite and red-brown anhydritic mudstone horizons.

10.6 Boundaries

10.6.1 Lower

The boundary with the underlying Main Röt Halite Member is discussed in section 9.6.2. Where this is absent, the Member directly overlies the Lower Röt Mudstone Member. This boundary is discussed in section 8.6.2.

Near the southern margin of the Anglo-Dutch Basin (Quadrant 53), the Main Röt Evaporite Member oversteps the Lower Röt Mudstone Member to lie directly on the Bunter Sandstone Formation (well 53/3-1, encl. Well J). Here the boundary is marked on the gamma-ray log by an abrupt increase in values, marking the change from the sandstones below, to the argillaceous dolomites and mudstones above.

10.6.2 Upper

The upper boundary is marked by a distinct change to higher gamma-ray and sonic log values, although the log profiles are highly serrated both above and below the contact (e.g. type well 48/12-1 and reference well 'Welton-1', encl. Well A and fig. 3.12 respectively). The FDC/SNP overlay shows a similar shift to higher LPU values, although the separation remains negative (e.g. encl. Well A).

A reduction in the amount of dolomite in the cuttings of encl. Wells G, H and I coincides with the top of the Member; however, this contact could not be determined on these logs alone.

The contact in the 'Staithes-20' well core (encl. Well B) is less obvious than that at the base of the Member (Plate 3.3). By comparison with the petrophysical logs, it occurs at the top of the last brecciated, silty dolomitic mudstone, and also marks the start of the

laminated dolomite/unlaminated mudstone couplets which form the Intermediate Röt Mudstone Member.

Locally in Quadrant 43, the dolomites/anhydrites in the upper part of the Member can be seen to pass laterally into the mudstones of the Intermediate Röt Mudstone Member, and hence this upper boundary is diachronous (fig. 3.6). This is not usually observed. In the area outside that of Main Röt Halite deposition, individual dolomitic/anhydritic horizons are difficult to correlate, and hence it is not possible to confirm any lateral gradation into the 'overlying' mudstones.

10.7 Thickness and Lateral Distribution

No isopach map is included for this Member due to the highly erratic thickness variations (listed in Appendix A, Table 1). These result from two main factors. First, there is a thickening of the Main Röt Evaporite Member outwards from the centre of the Main Röt Halite Member basin as individual halites pass laterally into the dolomites and anhydrites of the Main Röt Evaporite Member. This combines, secondly, with a thinning of the Member towards the margins as the individual dolomites/anhydrites gradually thin and possibly pass laterally into the overlying mudstones.

Some very general observations can be made. The Member is always between 3 - 23 metres thick. It has a maximum thickness of about 13 metres in the area where it is underlain by the Main Röt Halite Member, but is generally under 10 metres thick. Outside the Main Röt Halite basin, it is generally 8 - 18 metres thick, reaching a maximum of 23 metres.

10.8 Subdivision

The Member is not subdivided.

10.9 Correlation (encl. Map 5)

The Member equates with the non-halitic part of the Dutch Main Röt Evaporite Member of NAM/RGD (1980), and the non-halitic part of the Unteres Röt Salinar of Richter-Bernberg (1974) in north Germany. In both areas, the development is similar to that in the U.K. Southern North Sea area, both where the Member is underlain by the Main Röt Halite Member (encl. Wells L, M and N), and where this halite is absent (encl. Well K).

In East Germany, the Member equates with the Deckanhydrit of Docter *et al.* (1980) and in Poland with the Lower Gypsum Beds of Fuglewicz (1980). In the Danish area, the Member equates with part of the Ørslev Formation of Bertelsen (1980).

At outcrop in eastern England the Member equates with the Retford Formation (see Chapter 4), which in north-eastern England has alternatively been named the Seaton Carew Formation (Robson 1980).

11. INTERMEDIATE RöT MUDSTONE MEMBER (Dowsing Dolomitic Formation - New Member)

11.1 Type Well 48/12-1 (encl. Well A)

Depths: 4577' - 4632'

Thickness: 16.8 metres

11.2 Reference Well Staithes-20 (encl. Well B)

Depths: 1975' - 2031'

Thickness: 17.1 metres

11.3 Definition

A dolomitic and anhydritic mudstone unit of fairly constant thickness, lying between the Main Röt Evaporite Member and the Upper Röt Halite (or Evaporite) Members.

11.4 Remarks

The name is derived from the Intermediate Röt Claystone of the Dutch Sector (NAM/RGD 1980). Beyond the margins of the overlying Upper Röt Evaporite Member, the mudstones equivalent to this Member form the lower part of the Main Röt Mudstone Member (see section 15).

The proposed Member occurs both in the Dowsing Dolomitic Formation of the U.K. Southern North Sea, and in the proposed Dowsing Dolomitic Formation of the Mercia Mudstone Group in the subsurface of eastern England.

No enclosure Map is included for the Member. An isopach map for the U.K. Southern North Sea area is, however, shown on fig. 3.13.

11.5 Log Profiles and Lithologies

The Member shows highly serrated gamma-ray and sonic log profiles. The log values are generally higher than those in the surrounding Members, and are indicative of a more argillaceous succession

(e.g. type well 48/12-1, encl. Well A). Softer, caved lithologies are also indicated by cycle skipping on the sonic log (see Chapter 2, section 1.2.2), e.g. at the base of the Member in well 49/12-1 (encl. Well I).

A similar serrated profile with a negative separation is seen on the FDC/SNP overlay of the type well (encl. Well A). The high LPU values, combined with the negative separation, are indicative of mudstones, while the highly serrated profile indicates dolomitic, anhydritic (or even sandy) intercalations. This lithological interpretation is confirmed from the cuttings logs of wells 42/28-2, 48/6-2 and 49/12-1 (encl. Wells G, H and I), where the samples are dominated by red-brown mudstones. Green mottled mudstone, dark grey dolomite and anhydrite together account for a maximum of 35% (but generally less than 25%) of the sample.

In the cored 'Staithes-20' reference well (encl. Well B), the Member is composed of thin (up to 10 cm thick) green-grey argillaceous dolomites, with 0.5 cm to 5.0 cm thick interbedded dark green-grey and red-brown dolomitic mudstones (Plate 3.5). Interbedded with these thinly interlaminated units are generally unlaminated red-brown silty mudstones (0.5 to 3.5 metres thick). Nodular and vein anhydrite occurs throughout the Member (Plate 3.7). The origin of these laminated dolomites-mudstones/unlaminated mudstone couplets are discussed in Chapter 6 section 10.

11.6 Boundaries

11.6.1 Lower

The boundary is almost everywhere at the top of the Main Röt Evaporite Member, and is hence discussed in section 10.6.2. Only in well

47/5-1 does the Member directly overlie the Main Röt Halite Member. Here the boundary marks an abrupt upward change from blocky to higher, more serrated gamma-ray and sonic log profiles.

11.6.2 Upper

The upper boundary of the Member is marked by an abrupt change to lower gamma-ray and sonic values into both the overlying Upper Röt Halite Member (e.g. well 42/28-2, encl. Well G), or the Upper Röt Evaporite Member (type well 48/12-1, encl. Well A). A similar abrupt change is seen on the FDC/SNP overlays of encl. Wells A and B, although the log separation remains negative both above and below the boundary.

The boundary is not distinctive on the cuttings logs (e.g. encl. Wells G, H and I), or in the 'Staithes-20' well core (encl. Well B), where argillaceous laminated dolomites/mudstones and unlaminated mudstones occur both above and below the boundary. From comparison with the petrophysical logs, the boundary in the core is seen to mark the start of a much more anhydritic sequence.

11.7 Thickness and Lateral Distribution (fig. 3.13)

The Member is everywhere present beneath the Upper Röt Halite and Upper Röt Evaporite Members, and its lateral extent is determined by the recognition of this upper boundary (see the Upper Röt Evaporite Member margin on encl. Map 12). The Member has a fairly constant thickness, generally varying from 12 to 20 metres; within this range it shows a general thickening from eastern England towards Quadrant 44. Under eastern England, and towards its margins in the southern part of Quadrants 47, 48 and 49, the Member is 10 to 15 metres thick, while

locally, in the northern part of Quadrants 43 and 44, the Member is in excess of 20 metres thick. Thickness variations result in part from the lateral passage of the uppermost Main Röt Evaporite Member into the Intermediate Röt Mudstone Member (e.g. fig. 3.6).

11.8 Subdivision

The Member is not subdivided.

11.9 Correlation (encl. Map 12)

The Member equates with the Dutch Intermediate Röt Claystone Member of NAM/RGD (1980), and with the Zwischenmittel of Boigk (1959) in north Germany. In both areas, thickness and lithologies are similar to those in the U.K. Sector (e.g. encl. Wells K, M and N).

In East Germany, the Member is the lithostratigraphic equivalent of the Mergelstein und Dolomit of Dockter *et al.* (1980), while in Poland, it equates with the Inter-Gypsum beds of Fuglewicz (1980). No equivalent Member has been named in the Danish area (Bertelsen 1980).

At outcrop in eastern England part of the Colwick Formation forms the lithostratigraphic equivalent of the Member (see Chapter 4).

12. UPPER RöT HALITE MEMBER (Dowsing Dolomitic Formation - New Member)

12.1 Type Well 43/20-1 (fig. 3.6)

Depths: 4848' - 4877'

Thickness: 8.8 metres

12.2 Reference Well 42/28-2 (encl. Well G)

Depths: 5962' - 5980'

Thickness: 5.8 metres

12.3 Definition

A thin (up to 11 metres thick), correlatable halite unit, less extensive than the underlying Main Röt Halite Member, and passing laterally and vertically into the Upper Röt Evaporite Member.

12.4 Remarks

The Upper Röt Halite Member has not previously been named in the U.K. Southern North Sea (Rhys 1974). The name here proposed is adapted from the Dutch nomenclature (NAM/RGD 1980), where the Upper Röt Evaporite Member comprises this Member and the laterally equivalent dolomites and anhydrites. The Member is not present in the proposed Dowsing Dolomitic Formation of the Mercia Mudstone Group of eastern England, nor is it present in the U.K. Sector Dowsing Dolomitic Formation type well 48/12-1 (encl. Well A). An alternative type well (43/20-1) is proposed.

12.5 Log Profiles and Lithologies

The Member shows a distinctive blocky, low gamma-ray and sonic profile typical for halite, with Δt values close to the Δt_{ma} of 67 μ.sec/ft. Thin argillaceous horizons (higher gamma-ray/Δt values) and occasional anhydritic/dolomitic horizons (lower Δt values) are also

present (e.g. type well 43/20-1, fig. 3.6).

As the Member is not present in any of the wells with a FDC/SNP overlay, or in the cored 'Staithes-20' borehole, and as halite is not preserved in the samples of the one well containing the Member whose cuttings were logged (reference well 42/28-2, encl. Well G), the lithological interpretation is based solely on the gamma-ray and sonic logs.

12.6 Boundaries

12.6.1 Lower

This is everywhere the top of the Intermediate Röt Mudstone Member, discussed in section 11.6.2. The boundary may lie at the base of the halite or be separated from it by a thin dolomite or anhydrite (e.g. reference well 42/28-2, encl. Well G).

12.6.2 Upper

The boundary is placed at the top of the last halite, and marks a change from a blocky sonic log profile below to the more serrated profile of the Upper Röt Evaporite Member above. The gamma-ray log always shows a shift to higher values, while the sonic log may show a shift to lower Δt values where relatively clean dolomites/anhydrites immediately overlie the Member (e.g. reference well 42/28-2, encl. Well G), or a shift to higher Δt values where these are more argillaceously developed (e.g. type well 43/20-1, fig. 3.6).

12.7 Thickness and Lateral Distribution (encl. Map 12)

The Member is present in the northern part of the U.K. Southern North Sea, reaching a maximum thickness of 11 metres. Towards its margins, it thins and passes laterally into the dolomites and anhydrites of the Upper Röt Evaporite Member.

Deposition was essentially restricted to the east of the Dowsing Fault Zone, and only extends west of this in the area to the north of latitude 54°N, where its western limit approximately coincides with the present-day coastline. The Member is absent over the remainder of the East Midlands Shelf.

12.8 Subdivision

In many, but not all, wells the Member can be subdivided into two units separated by a thin (higher gamma-ray) mudstone. The lower unit is generally only 1 to 2 metres thick, and may not always be halitic, while a much thicker halite forms the upper unit (fig. 3.6). A cyclicity, similar to that seen within the Main Röt Halite Member, is proposed (Chapter 6 section 9).

12.9 Correlation (encl. Map 12)

The Member equates with the halitic part of the Dutch Upper Röt Evaporite Member of NAM/RGD (1980), and the halitic part of the Oberes Rötsalinar of Richter-Bernberg (1974) in north Germany. In both areas it shows a similar thickness to that recorded in the U.K. Sector.

The Member's equivalent cannot be identified from the logs

presented by Michelsen and Andersen (1983) for the Danish area, or on the East German correlation panels of Dockter *et al.* (1980). Fuglewicz (1980) and Tokarski (1965) likewise do not report the presence of halite at this horizon in Poland.

13. UPPER RöT EVAPORITE MEMBER (Dowsing Dolomitic Formation New Member)

13.1 Type Well — 48/12-1 (encl. Well A)
Depths: 4560' - 4577'
Thickness: 5.2 metres

13.2 Reference Wells — 42/28-2 (encl. Well G)
Depths: 5938' - 5961'
Thickness: 7.0 metres

Staithes-20 (encl. Well B)
Depths: 1965' - 1975'
Thickness: 3.1 metres

13.3 Definition

A sequence of dolomites, anhydrites and dolomitic/anhydritic mudstones, surrounded by the Intermediate and Upper Röt Mudstone Members, and laterally equivalent to, and partly underlain by, the Upper Röt Halite Member.

13.4 Remarks

The name is adopted from the Dutch Upper Röt Evaporite Member of NAM/RGD (1980), although the Dutch Member locally includes the halites which in the U.K. Sector are proposed as the Upper Röt Halite Member.

The Member occurs both in the Dowsing Dolomitic Formation of the U.K. Southern North Sea, and in the proposed Dowsing Dolomitic Formation of the Mercia Mudstone Group in the subsurface of eastern England.

13.5 Log Profiles and Lithologies

The Member shows serrated gamma-ray and sonic log profiles, with log values lower than those of the underlying and overlying mudstone Members (e.g. type well 48/12-1, encl. Well A). These profiles, along with the generally lower LPU values and negative separation on the FDC/SNP overlays (encl. Wells A and B), are indicative of a more dolomitic/anhydritic unit than those above and below. The Member becomes increasingly difficult to recognise on the logs towards its margins, where it passes laterally into the mudstones of the Main Röt Mudstone Member (fig. 3.14).

The Member does not appear at all distinctive on the cuttings log of encl. Well H, and encl. Wells G and I show only minor increases in the dolomite percentage. Mudstone cavings dominate the cuttings in all three wells.

In the cored 'Staithes-20' reference well (encl. Well B), the Member is composed of green to brown-grey argillaceous dolomites with interbedded red-brown silty, dolomitic mudstones, frequently with nodular

anhydrite (Plate 3.9). This reference well lies towards the margin of the Members development (encl. Map 12), and hence the lithologies present may not be typical of the Member as a whole.

13.6 Boundaries

13.6.1 Lower

This boundary occurs at the top of the Intermediate Röt Mudstone Member, as in the type well 48/12-1 (encl. Well A), and is discussed in section 11.6.2. The Member also overlies the Upper Röt Halite Member (e.g. reference well 42/28-2, encl. Well G); and this boundary is discussed in section 12.6.2.

13.6.2 Upper

The boundary is marked by an abrupt change to the higher gamma-ray and sonic log values of the Upper Röt Mudstone Member (type well 48/12-1, encl. Well A). The contact is distinct and easily recognised, except close to the limit of the Members development. On the FDC/SNP overlay an abrupt change to higher LPU values marks the boundary, although the log separation remains negative.

In the more marginal 'Staithes-20' reference well (encl. Well B), the boundary is clear on the logs, but less so in the core. By comparison with the logs, the boundary is seen to coincide with the junction between a more dolomitic/anhydritic succession below and a less dolomitic/anhydritic succession above. Red-brown mudstones dominate both above and below the boundary.

13.7 Thickness and Lateral Distribution

No isopach map is included for the Member, although the thicknesses are listed in Appendix A, Table 1. The Member is almost everywhere 3 to 6 metres thick. It is at its thickest near the Upper Röt Halite Member basin, and thins away from this towards its margin, where it passes laterally into the Main Röt Mudstone Member. The lateral extent of the Member is shown on encl. Map 12.

The southern limit of the Member runs approximately east-west from just south of the River Humber, across the middle of Quadrants 47, 48 and 49. There is no margin against the Cleaver Bank High, and the Member is locally present in the Southern Dutch Sector. Any northern limit to the Member has been removed by post-Triassic uplift and erosion along the Mid-North Sea High. The margin has, however, been preserved between the wells 'Staithes-20' and 41/8-1 in the north-east of the area.

13.8 Subdivision

The Member is not subdivided.

13.9 Correlation (encl. Map 12)

The Member equates with the non-halitic part of the Upper Röt Evaporite Member of the Dutch nomenclature (NAM/RGD 1980). A marginal development of the Member is seen in Dutch Well K/13-1 (encl. Well K). Similarly, in north Germany, the equivalent of the Member is the non-halitic part of the Oberes Rötsalinar of Richter-Bernberg (1974), seen in encl. Wells M and N.

The Member's equivalent is not identified in the Danish wells presented in Bertelsen (1980) and Michelsen and Andersen (1983). In East Germany the Member equates with the 'Gips und Anhydrit Banken' overlying the 'Mergelstein und Dolomit' of Dockter *et al.* (1980), while in Poland it equates with the Upper Gypsum Beds of Fuglewicz (1980).

14. UPPER RöT MUDSTONE MEMBER (Dowsing Dolomitic Formation - New Member)

14.1 Type Well 48/12-1 (encl. Well A)

Depths: 4350' - 4560'

Thickness: 64.0 metres

14.2 Reference Well Staithes-20 (encl. Well B)

Depths: 1870' - 1965'

Thickness: 28.9 metres

14.3 Definition

A dolomitic mudstone succession with silty and anhydritic mudstones and occasional thin argillaceous dolomites, lying between the Upper Röt Evaporite Member and the Muschelkalk Dolomitic Member.

14.4 Remarks

The name is derived from the Upper Röt Claystone Member of the Dutch nomenclature (NAM/RGD 1980). In those areas where the Upper Röt Halite/Evaporite Members are absent, this Member is inseparable from the

Intermediate Röt Mudstone Member, and hence the two Members are combined as the Main Röt Mudstone Member (see section 15).

The Upper Röt Mudstone Member occurs both in the Dowsing Dolomitic Formation of the U.K. Southern North Sea, and in the proposed Dowsing Dolomitic Formation of the Mercia Mudstone Group of the sub-surface eastern England.

14.5 Log Profiles and Lithologies

On the gamma-ray and sonic logs, the Member is dominated by generally high values and a highly serrated profile. The FDC/SNP overlay shows a similar profile and a negative separation (type well 48/12-1, encl. Well A). The Member has the same general profile throughout the U.K. Southern North Sea area, both towards the centre of the basin, where it is over 60 metres thick (e.g. type well 48/12-1, encl. Well A), and towards the margin where it is under 30 metres thick (e.g. reference well 'Staithes-20', encl.Well B).

The profiles, along with cycle-skipping on the sonic log (very high Δt peaks), are indicative of a soft, caved mudstone sequence. The intervening low Δt peaks suggest more dolomitic/anhydritic zones, which may be discrete thin beds (below the resolution of the logging tool), or intermixed lithologies. This cannot be determined from the logs.

The cuttings logs of encl. Wells G, H and I are dominated by red-brown mudstones with occasional dark green mudstones. Anhydrite and dolomite rarely account for more than 20% of the sample, and are usually 10% or less.

The predicted lithologies are confirmed by the cored 'Staithes-20' well (encl. Well B). The Member is composed primarily of

dark red-brown mudstones, with occasional thin interbedded green-grey argillaceous dolomites. The mudstones are frequently silty, dolomitic and anhydritic. The lower half of the Member (which includes a 14' (4.3 metres) break in the core) is dominated by generally unlaminated red-brown anhydritic mudstones, with rare interbedded thin dolomites. The upper part of the Member (above 1921' core depth) shows a greater degree of lamination (Plate 3.11). The laminated dolomite-mudstone/unlaminated mudstone couplets seen in the Intermediate Röt Mudstone Member are again evident in the upper part of this Member, and once again are discussed in Chapter 6.

14.6 Boundaries

14.6.1 Lower

This is everywhere the top of the Upper Röt Evaporite Member (see section 13.6.2).

14.6.2 Upper

This boundary, marking the top of the Röt succession, is the same as the top of the Main Röt Mudstone Member. The two are discussed together in section 15.6.2.

14.7 Thickness and Lateral Distribution

No isopach map is presented for the Member. Encl. Map 13 shows the thickness distribution of the Main Röt Mudstone Member plus the combined thickness of the laterally equivalent Intermediate and Upper Röt Mudstone Members. As the thickness variations in the Intermediate Röt

Mudstone Member are only slight (section 11.7), encl. Map 13 essentially reflects variations in the Upper Röt Mudstone Member. This thickness distribution is discussed under the Main Röt Mudstone Member (section 15.7).

14.8 Subdivision

As noted in section 14.5, a subdivision is possible in the 'Staithes-20' well core (encl. Well B), into an unlaminated lower part and a more laminated upper part. This subdivision, however, cannot be linked to a distinct log profile and hence cannot be extended into the uncored wells.

14.9 Correlation (encl. Map 13)

The Upper Röt Mudstone Member equates with the Dutch Upper Röt Claystone Member of NAM/RGD (1980), and the north German Röt-Tone of Richter-Bernberg (1974). Although thicknesses differ, the log profiles in these areas are similar to those in the U.K. Sector (encl. Wells K, M and N). The subdivision in north Germany into the Rotbraune and Grauviolette Gruppen (Boigk 1959, Hinze 1967), has been observed in encl. Wells M and N.

In East Germany, the Member equates with the Pelitröt of Dockter *et al.* (1980), and in Poland it equates with the Supra-Gypsum Beds of Fuglewicz (1980). In the Danish area the Member is the equivalent of part of the Ørslev Formation of Bertelsen (1980).

At outcrop in eastern England the Member equates with the upper part of the Colwick Formation of Warrington *et al.* (1980), except in the

most marginal areas. This is discussed in Chapter 4.

15. MAIN RöT MUDSTONE MEMBER (Dowsing Dolomitic Formation - New Member)

15.1 Type Well 49/26-4 (fig. 3.15)

Depths: 2590' - 2865'

Thickness: 81.1 metres

15.2 Reference Well Welton-1 (fig. 3.12)

Depths: 519 - 573 metres

Thickness: 54.0 metres

15.3 Definition

A dolomitic silty mudstone sequence with occasional thin argillaceous dolomites, identical and laterally equivalent to the Intermediate and Upper Röt Mudstone Members.

15.4 Remarks

This name is proposed in those areas where the Röt Mudstone Members cannot be separated due to the absence of the Upper Röt Halite/ Evaporite Members.

The Member is present in both the Dowsing Dolomitic Formation of the U.K. Southern North Sea, and the proposed Dowsing Dolomitic Formation of the Mercia Mudstone Group of the subsurface of eastern England. The Member is not present in the Dowsing Dolomitic Formation

type well 48/12-1, or in reference well 'Staithes-20'. Alternative type and reference wells are hence proposed.

15.5 Log Profiles and Lithologies

The Member is not present in any of the wells whose cuttings were logged. The gamma-ray, sonic and FDC/SNP log profiles are very similar to those of the Intermediate and Upper Röt Mudstone Members, and the Member is hence likewise considered to be a mudstone dominated sequence with local dolomitic, silty and anhydritic horizons. The type well 49/26-4 (fig. 3.15) shows typical serrated gamma-ray and sonic log profiles, and well 53/7-2 (encl. Well E) shows the FDC/SNP overlay.

15.6 Boundaries

15.6.1 Lower

Except in the most marginal areas, this boundary coincides with the top of the Main Röt Evaporite Member (discussed in section 10.6.2). In Quadrants 52 and 53, the Member oversteps the Main Röt Evaporite Member to lie directly on the Bunter Sandstone Formation (e.g. well 53/7-2, encl. Well E). Here the boundary is marked by an abrupt change to higher gamma-ray log values and a switch from a positive to a negative separation on the FDC/SNP overlay.

15.6.2 Upper

This marks the boundary between the Röt and Muschelkalk successions. It is identical to the upper boundary of the Upper Röt Mudstone Member, and hence both boundaries are discussed here.

Despite previous assertions that any separation between the Röt and Muschelkalk successions in the U.K. Sector "would be artificial and incapable of sustaining over any distance" (Rhys 1975, p.157), this boundary is distinct throughout most of the U.K. Southern North Sea area.

On the gamma-ray and sonic logs the boundary separates two highly serrated profiles, the overlying having generally lower log values (e.g. well 48/12-1, encl. Well A). In detail the boundary occurs at an abrupt change to lower gamma-ray and sonic log values, marking the base of a 2 to 5 metre-thick zone with a somewhat less serrated profile. This zone, underlain by the Upper/Main Röt Mudstone Member, and overlain by a zone of higher gamma-ray and sonic values within the Muschelkalk Dolomitic Member, forms a highly distinctive, regionally correlative marker. That the base of this marker is truly the lithostratigraphic equivalent of the top of the Dutch Röt Formation is shown by correlation with the Dutch wells (fig. 3.16). This in turn has been equated litho-stratigraphically with the top of the Röt in north Germany (encl. 11 of NAM/RGD 1980), as shown on fig. 6.10.

It is only in Quadrant 53, where this marker horizon becomes difficult to recognise, that the boundary between the Röt and Muschelkalk successions is difficult to determine. Lateral correlation southwards into this area allows a tentative boundary to be determined (e.g. in wells 53/4-4 and 53/7-2, encl. Wells D and E). Throughout the remainder of the U.K. Southern North Sea area, the boundary is very distinctive, e.g. wells 49/12-1, 42/28-2 and 'Staithes-20' (encl. Wells I, G and B respectively). In Chapter 4, it will be shown that the boundary can be traced right to outcrop in eastern England. On the FDC/SNP overlay, an abrupt shift to generally lower LPU values marks the boundary in well 48/12-1 (encl. Well A), although it is less distinct on the other

overlays (encl. Wells B, D and E).

On the cuttings logs, the boundary is marked by an abrupt increase in the amount of grey dolomite from around 10% to 30% (encl. Wells G, H and I). Even at first glance the samples show a marked colour change at this boundary (red-brown still dominates, but there is a distinct greyish hue above the contact).

In the 'Staithes-20' well core (encl. Well B), this is a very distinct boundary, marking a major colour change from a dominantly red-brown succession below, to a succession with far more green-grey beds above. The boundary itself coincides with the base of a dominantly light green-grey laminated dolomite, approximately 3 metres thick, which corresponds with the low gamma-ray/sonic log marker described above. Although green-grey dolomites occur below the boundary, these are well separated and less than 0.5 metres thick.

15.7 Thickness and Lateral Distribution (encl. Map 13)

Enclosure Map 13 for the Main Röt Mudstone Member is a composite, showing the thickness of the Main Röt Mudstone Member where present and, in other areas, the combined thickness of the Intermediate and Upper Röt Mudstone Members. Thickness variations are best considered separately in the three main structural areas.

15.7.1 East Midlands Shelf

The Member is usually between 45 and 65 metres thick. It shows a very gradual increase in thickness to over 60 metres in the offshore area around latitude 54° North.

The Member thins rapidly from 40 metres to under 20 metres in

Quadrants 52 and 53. This rapid thinning is the result of progressive onlap onto the Bunter Sandstone Formation towards the margin. Thicknesses are somewhat suspect in this area, due to the absence of the distinctive marker at the base of the Muschelkalk Dolomitic Member. At its thinnest, the Member is tentatively identified as 12 metres thick in well 53/12-3 (encl. Well F).

15.7.2 Anglo-Dutch Basin/Broad Fourteens Basin

Thicknesses vary between 40 and 90 metres in the Anglo-Dutch Basin. In the southern part of the Basin, the 40 and 60 metre isopachs closely parallel the Dowsing Fault Zone, close to which the Member, in part, thins due to progressive onlap onto the Bunter Sandstone Formation (e.g. well 53/7-2, encl. Well E).

The Member is slightly thicker in the proposed U.K. Broad Fourteens Basin compared with the Anglo-Dutch Basin. The greatest thickness of the Member in the U.K. Southern North Sea is found in this area (107 metres in well 43/20-1), and two other wells show thicknesses in excess of 91 metres (wells 44/19-2 and 44/26-1). No wells in the Anglo-Dutch Basin exceed this thickness.

15.8 Subdivision

The Member is not subdivided.

15.9 Correlation (encl. Map 13)

The Members lithostratigraphic equivalents are the same as the combined equivalents of the Intermediate and Upper Röt Mudstone Members.

16. MUSCHELKALK DOLOMITIC MEMBER (Dowsing Dolomitic Formation-New Member)

16.1	Type Well	48/12-1	(encl. Well A)
			Depths: 4150' - 4350'
			Thickness: 61.5 metres
16.2	Reference Wells	43/17-1	(fig. 3.17)
			Depths: 1775' - 1983'
			Thickness: 63.6 metres
		Staithes-20	(encl. Well B)
			Depths: 1750' - 1870'
			Thickness: 36.6 metres

16.3 Definition

A sequence of interbedded dolomites and dolomitic mudstones, occasionally anhydritic, and very locally halitic, sitting between the Upper/Main Röt Mudstone Member and the Muschelkalk Halite/Muschelkalk Evaporite Members.

16.4 Remarks

The name Lower Muschelkalk Member is not adopted from the Dutch nomenclature as the U.K. Sector Member is lithologically different from the marly micritic limestones of the Unterer (Lower) Muschelkalk in the type area of north Germany. A new name, the Muschelkalk Dolomitic Member is proposed.

The Member is present in both the Dowsing Dolomitic Formation of the U.K. Southern North Sea, and in the proposed Dowsing Dolomitic Formation of the Mercia Mudstone Group of the subsurface eastern England.

16.5 Log Profiles and Lithologies

The gamma-ray and sonic logs, and the FDC/SNP overlay, show a highly serrated profile throughout the Member. There is a general shift to lower log values and a more serrated profile than in the underlying Upper/Main Röt Mudstone Member. This is clearly seen in the type well 48/12-1 (encl. Well A), and in reference well 'Staithes-20' (encl. Well B).

The serrated log profiles, along with the negative separation on the FDC/SNP overlay, are indicative of a sequence of dolomites with interbedded argillaceous units. This interpretation is supported by the cuttings logs of encl. Wells G and H which, although dominated by red-brown mudstones (mostly cavings?), do contain up to 35% dolomite. White amorphous anhydrite in the samples (generally up to 10%) may represent both in situ lithologies and cavings.

In the 'Staithes-20' well core, the Member comprises of green-grey argillaceous dolomites interbedded with red-brown silty mudstones. Dolomitic horizons generally contain argillaceous interbeds (Plate 3.12) and red-brown mudstone horizons contain dolomite layers (Plate 3.17). Anhydrite occurs locally both as veins and nodules. Although there is an alternation of dolomite and mudstone dominated horizons, repeated distinct couplets (as seen in the Intermediate and Upper Röt Mudstone Members) are less obvious in this Member.

Reference well 43/17-1 shows an unusual development of halite

in the Member, which is only seen for certain in this well and well 43/21-1 (fig. 3.17). The halite beds are identified from their sonic log values of close to 67 μ.sec/ft (Δt_{ma} for halite) and confirmed by the FDC log values approaching 1.04 gm/cc (ρ_{ma} for halite). Individual halite beds, generally less than 5 metres thick, occur at several horizons within the Member. Although one halite bed is correlatable between the two wells, the other halites appear to occur at different horizons in each well. Halite may also be locally present in well 44/21-1 (also shown on fig. 3.17), but in the absence of a FDC log, this is based solely on a more blocky profile (at 4370' depth) with a Δt approaching 67 μ.sec/ft.

16.6 Boundaries

16.6.1 Lower

This is everywhere the contact with the Upper/Main Röt Mudstone Member, and is described in section 15.6.2.

16.6.2 Upper

The boundary is placed at the base of the Muschelkalk Halite Member, or its lateral equivalent the Muschelkalk Evaporite Member. In the vast majority of wells, an up to 10 metres thick, dominantly argillaceous 'marker' horizon (with higher gamma-ray and sonic values) occurs immediately below the boundary (e.g. type well 48/12-1 and reference well 'Staithes-20', encl. Wells A and B respectively).

Where the Member is overlain by the Muschelkalk Halite Member, the boundary is marked by an abrupt upward change to lower gamma-ray and sonic log values, and a change from a highly serrated to a smoother, more blocky log profile (e.g type well 48/12-1, encl. Well A). This boundary

is only seen on the FDC/SNP overlay of this well where, despite severe corruption of these logs above the contact (due to washout), it is marked by a change from a negative to a positive separation.

On the cuttings log of well 48/6-2 (encl. Well H), the boundary is marked by a rapid upwards decrease in the percentage of red-brown mudstone in the samples (from 85% below the boundary to 10% above). The contact is blurred by halite cavings.

Where the Member is overlain by the Muschelkalk Evaporite Member (e.g. reference well 'Staithes-20' and well 53/7-2, encl. Wells B and E respectively), there is once again a marked change to lower gamma-ray and sonic log values, and to lower LPU values on the FDC/SNP overlay. The profiles remain serrated, and the overlay separation remains negative. The cuttings log for well 42/28-2 (encl.Well G) also shows the boundary very clearly with an abrupt change from 60% dolomite and anhydrite above the contact to 10% immediately below. Unusually, this contact is not blurred by caving.

The boundary is not immediately obvious in the core of the 'Staithes-20' well (encl. Well B). However, correlation with the petro-physical logs shows it to occur at the top of a 4 metre-thick mudstone, and to be immediately overlain by an irregular argillaceous anhydritic dolomite, which passes upwards into a patchily dolomitised mudstone (Plate 3.20).

16.7 Thickness and Lateral Distribution (encl. Map 14)

The Muschelkalk Dolomitic Member is everywhere present in the U.K. Southern North Sea area, and in general shows a simple concentric thickening towards Quadrant 44. The Member does not show any evidence of

thinning towards the Cleaver Bank and Mid-North Sea Highs. Thickness variations do, however, occur between the three main structural elements.

Across the East Midlands Shelf, the Member shows only a very gradual thickening from about 30 metres near Nottingham to 54 metres close to the Dowsing Fault Zone in the north of Quadrant 47.

Immediately across the Dowsing Fault Zone, however, in the Anglo-Dutch Basin, the Member thickens much more rapidly from around 46 metres to over 62 metres, with the 50 and 60-metre isopachs paralleling the fault zone. To the east of the 60-metre isopach, thicknesses vary little across the remainder of the Anglo-Dutch Basin, with one exception: at 69 metres, well 47/5-1 shows the thickest development of the Member within this basin, in the area of the Sole Pit Trough.

Thicknesses increase again slightly into the proposed U.K. Broad Fourteens Basin, with the 70 metre isopach restricted to this area.

16.8 Subdivision

A four-fold vertical subdivision can be identified within the Muschelkalk Dolomitic Member in the type well 48/12-1 (encl. Well A). From the base up, the four units are firstly, Unit 1, a dominantly dolomitic unit about 5 metres thick, characterised on logs by low gamma-ray and sonic values. This forms the distinct 'marker' dolomite which is present at the base of the Member over most of the U.K. Southern North Sea area (see section 15.6.2). This is overlain by Unit 2, a mudstone-dominated sequence about 9 metres thick in the type well, which is characterised by generally high gamma-ray and sonic values. While the lower boundary of Unit 2 is distinct, the upper boundary is somewhat more gradational with an increase in dolomite interbeds. The result is a

transition to Unit 3, a sequence of dolomite and mudstone interbeds, producing highly serrated gamma-ray and sonic log profiles. (The dolomite/mudstone ratio is approximately 60:40.) This unit is approximately 41 metres thick, forming the majority of the Member. The upper boundary is again somewhat gradational with the final unit, Unit 4, which is once again a mudstone dominated sequence characterised by high gamma-ray and sonic values. This unit is approximately 6 metres thick and its top forms the top of the Member.

This four-fold subdivision can be recognised in the majority of wells in the U.K. Southern North Sea area (e.g. fig. 3.15). Usually it is clear, although Unit 2 may be difficult to separate from Unit 3 (as in well 42/28-2, encl. Well G), and southwards in Quadrants 52 and 53 Unit 1 becomes increasingly difficult to recognise. (Note: the subdivision can still tentatively be made in wells 52/5-2 and 53/7-2 (encl. Wells C and E respectively).

Guided by the logs, the subdivision can be identified in the core of the 'Staithes-20' well (encl. Well B), where a very distinctive, dominantly dolomitic Unit 1 (Plate 3.12) is overlain by a mudstone dominated Unit 2 and the interbedded dolomites and mudstones of Unit 3. Dolomite is almost totally absent from the final mudstone unit, Unit 4.

16.9 Correlation

Unlike the lower Members of the Dowsing Dolomitic Formation, this Member does not show a similar lithological development right across the basin, but rather grades laterally into the micritic limestones and marls of north Germany. The lithostratigraphic equivalents of the Member are hence defined by the confining boundaries of the underlying and

overlying Members rather than internal lithological similarities.

The Member equates with the Lower Muschelkalk Member of the Dutch nomenclature of NAM/RGD (1980). In the north-west of the Southern Dutch Sector, this Member has a similar development to that of the Muschelkalk Dolomitic Member (e.g. well K/13-1, encl. Well K), while towards the south-east a much more dolomitic profile is encountered (e.g. well Q/4-1, encl. Well L). Further to the east, in eastern Holland, the Member comprises marly limestones with interbedded dolomites (de Boorder *et al.* 1985).

In north Germany, thinly bedded marly limestones of the Unterer Muschelkalk of Wolburg (1969) form the lithostratigraphic equivalent of the Muschelkalk Dolomitic Member. Other authors (Trusheim 1971) have placed the top a few metres lower, at the base of an argillaceous unit, as shown on encl. Wells M and N. In East Germany, the Member again equates with the Unterer Muschelkalk, or Wellenkalk-Folge of Docter *et al.* (1980). The correlation to logs is shown by Althen *et al.* (1980). In the Polish area, the Member equates with the Lower Muschelkalk of Senkowiczowa (1961), while in the Danish area it forms the lower part of the Falster Formation of Bertelsen (1980).

At outcrop in eastern England, the Member equates with the Radcliffe Formation of Warrington *et al.* (1980). Towards the margin it equates with the diachronous Colwick Formation, as discussed in Chapter 4.

17. MUSCHELKALK HALITE MEMBER (Dowsing Dolomitic Formation - Previously Defined Member)

17.1 Type Well 48/12-1 (encl. Well A)

Depths: 3969' - 4150'

Thickness: 55.2 metres

17.2 Reference Well 49/26-4 (fig. 3.15)

Depths: 2220' - 2413'

Thickness: 58.5 metres

17.3 Definition

A succession of thick halite beds, occasionally dolomitic/anhydritic, interbedded with thin anhydrites, dolomites and mudstones.

17.4 Remarks

This Member was defined by Rhys (1974). Its boundaries (*idem* 1975) are the same as those proposed here, but the Triassic type well 49/12-1 (fig. 3.2) is not here used as the type well for the Member as the lower part is faulted out (fig. 3.3). The Member is not present in the proposed Dowsing Dolomitic Formation of the Mercia Mudstone Group of eastern England.

17.5 Log Profiles and Lithologies

In the type well 48/12-1 (encl. Well A), the Member shows a

generally smooth, blocky gamma-ray and sonic log profile, with Δt values lying close to 67 μ.sec/ft (Δt_{ma} for halite). Thin, 1 to 2 metres thick, zones of higher gamma-ray values are interpreted as interbedded mudstones. On the sonic log these zones are partly obscured by very thin, extremely high and low Δt peaks which result from severe borehole washout. This washout also results in the highly corrupted FDC/SNP overlay. The Member shows the same general profile throughout its area of deposition (e.g. reference well 49/26-4, fig. 3.15).

Halite is preserved in the cuttings of well 48/6-2 (encl. Well H), confirming the general lithology. The greater percentage of halite in the samples from the lower part of the Member is more likely to be an artefact of drilling, rather than a true lithological variation. Red-brown mudstone cavings once again dominate.

17.6 Boundaries

17.6.1 Lower

This is everywhere the top of the Muschelkalk Dolomitic Member, and is hence discussed in section 16.6.2. As with the Main Röt Halite Member, the boundary may occur at the base of the first halite bed (e.g. type well 48/12-1, encl. Well A), or at the base of a thin anhydrite/ dolomite which either immediately underlies this, or is separated from it by a thin mudstone (e.g. well 48/6-2, encl. Well H).

17.6.2 Upper

The boundary with the Muschelkalk Evaporite Member is marked by an abrupt change from blocky to serrated gamma-ray and sonic log profiles. This is usually accompanied by a shift to slightly higher

values (e.g. type well 48/12-1 and reference well 49/26-4, encl. Well A and fig. 3.15 respectively). The boundary also coincides with the end of the zone of severe borehole washout in the type well, and hence is marked by a return to a valid negative separation on the FDC/SNP overlay.

The boundary is not very distinct on the cuttings log of encl. Well H, due to mudstone cavings. There is, however, an increase in the percentage of dolomite upwards into the Muschelkalk Evaporite Member (from 15% below the contact, to 30% immediately above).

17.7 Thickness and Lateral Distribution (encl. Map 15)

The present distribution of the Member in the U.K. Southern North Sea is in a single basin with a surrounding margin which runs along the Dowsing Fault Zone, and then parallels the Mid-North Sea High and the Cleaver Bank High. The Member is generally absent from the East Midlands Shelf, although it is present in one well (well 41/20-1).

The main area of deposition lies east of the Dowsing Fault Zone, in the Anglo-Dutch Basin and the proposed U.K. Broad Fourteens Basin, where it rapidly thickens from its margins to about 40 metres (over 60 metres in the Sole Pit area) and then gradually thickens over the centre of the basin to around 55 to 65 metres. This Member does not show a thicker development in the Broad Fourteens Basin.

The origin of the present basin margins (depositional v. post-depositional) is discussed in Chapter 6 section 12.

17.8 Subdivision

The Member can be subdivided vertically into a series of halite

units on the basis of the thin high gamma-ray mudstone interbeds (e.g. type well 48/12-1, encl. Well A). Such a subdivision is possible in all the wells (e.g. reference well 49/26-4, fig. 3.15), but correlation between wells is much more difficult than in the Main Röt Halite Member. Hence no formal subdivision of the Member is proposed. One thin halite bed in the middle of the Member (marked * on encl. Well A and fig. 3.15) is frequently correlatable.

17.9 Correlation (encl. Map 15)

The Member equates with the Muschelkalk Salt of the Dutch nomenclature (NAM/RGD 1980) and with the Mittlerer Muschelkalk Salinar of north Germany (Schröder 1982, Trusheim 1971, Wolburg 1969). Both litho-stratigraphic equivalents show a development and thickness similar to that in the U.K. Sector (e.g. well Q/4-1 (encl. Well L) and well 'Ems River Mouth' (encl. Well M)). In the Danish Central Graben, the Member equates with the Muschelkalk Halite Member of Jacobsen (1982), while over the remainder of the Danish area no equivalent halites are present (Bertelsen 1980).

In East Germany, the Member equates with the halites of the 'Anhydrit mit Steinsalz' of Dockter *et al.* (1980). No equivalent halites are present in the Polish area (see maps of Schröder 1982 and Ziegler 1982a).

18. MUSCHELKALK EVAPORITE MEMBER (Dowsing Dolomitic Formation-New Member)

18.1	Type Well	48/12-1	(encl. Well A)
			Depths: 3922' - 3969'
			Thickness: 14.3 metres
18.2	Reference Wells	42/28-2	(encl. Well G)
			Depths: 5581' - 5642'
			Thickness: 18.6 metres
		Staithes-20	(encl. Well B)
			Depths: 1703' - 1750'
			Thickness: 14.3 metres

18.3 Definition

A sequence of dolomites and anhydrites with interbedded dolomitic and anhydritic mudstones, overlying and laterally equivalent to the Muschelkalk Halite Member.

18.4 Remarks

The name Muschelkalk Evaporite Member is proposed to conform with the similarly proposed Main Röt Evaporite and Upper Röt Evaporite Members, which occur lower in the Dowsing Dolomitic Formation.

The Member occurs both in the Dowsing Dolomitic Formation of the U.K. Southern North Sea, and in the proposed Dowsing Dolomitic Formation of the Mercia Mudstone Group of the subsurface of eastern

England.

18.5 Log Profiles and Lithologies

Similar log profiles are seen both where the Member is underlain by the Muschelkalk Halite Member (e.g. type well 48/12-1, encl. Well A), and in those areas where this is absent (e.g. reference well 42/28-2, encl. Well G).

In the type well 48/12-1 (encl. Well A), the Member exhibits a highly serrated gamma-ray and sonic log profile, with log values generally lower than those in the overlying Muschelkalk Mudstone Member. A similar profile, with a negative separation, is seen on the FDC/SNP overlay. As with the Main and Upper Röt Evaporite Members, these profiles are interpreted as due to a succession of anhydrites/dolomites and inter-bedded anhydritic/dolomitic mudstones. The cuttings log of well 48/6-2 (encl. Well H) is in agreement with this interpretation, showing up to 35% dolomite and anhydrite.

Outside the area of Muschelkalk Halite Member deposition, but close to its margin, the Muschelkalk Evaporite Member is distinct and easy to identify (e.g. reference well 42/28-2 (encl. Well G) and well 53/4-4 (encl. Well D)). The cuttings of the former well show up to 65% dolomite and anhydrite in the samples. Further away from the halite margin, the Member becomes increasingly difficult to recognise but is at least tentatively identified in all the wells studied in the U.K. Southern North Sea area. The 'Staithes-20' reference well (encl. Well B) shows this marginal development. It is reflected in the core, where irregularly developed dolomites (Plate 3.20) and anhydrites (Plate 3.21) are interbedded in a silty, dolomitic mudstone dominated sequence.

18.6 Boundaries

18.6.1 Lower

This either coincides with the top of the Muschelkalk Dolomitic Member (see section 16.6.2) or the Muschelkalk Halite Member (see section 17.6.2).

18.6.2 Upper

This boundary occurs everywhere at the base of the Muschelkalk Mudstone Member and is marked on the gamma-ray and sonic logs by a shift of the serrated profiles to generally higher log values. This shift is most clearly seen on the sonic log (e.g. type well 48/12-1 (encl. Well A) and reference well 42/28-2 (encl. Well G)). In the former well, the boundary is enhanced by the severe caving in the overlying Member and the resulting cycle skipping. The FDC/SNP overlays show a similar profile across the boundary, e.g. type well 48/12-1, and well 53/7-2 (encl. Wells A and E respectively).

The boundary is not marked in the cuttings of well 42/28-2 (encl. Well G), although in well 48/6-2 (encl. Well H) there is a slight decrease in the percentage of dolomite and anhydrite across the boundary (from 15% immediately below to 5% immediately above).

The marginal position of the reference well 'Staithes-20' (encl. Well B) results in a very poorly defined boundary in the core. From log correlation, it is placed at the top of particularly anhydritic mudstone horizon, which is over- and underlain by mudstones. It is possible, however, that the boundary occurs 4.5 metres lower, at the top of a distinctive dolomite horizon (as indicated on encl. Well B).

18.7 Thickness and Lateral Distribution

No enclosure Map is included for this Member, however the thickness distribution for the U.K. Southern North Sea area is shown on fig. 3.18.

The Member is everywhere between 8 and 24 metres thick, with a thickness distribution that is closely related to the distribution of the Muschelkalk Halite Member. Where this is present, the Member thickens from under 10 metres (over the centre of the Muschelkalk Halite Member basin) to 15 metres close to the halite margin. It then continues to thicken immediately beyond this margin. Farther towards the north-west, the Member then thins again to about 14 metres, while towards the south-west, it thickens to over 20 metres.

The overall thickening of the Member from the centre of halite deposition towards its margins and immediately beyond, is strong evidence that the individual halites of the Muschelkalk Halite Member pass laterally into the dolomites and anhydrites of the Muschelkalk Evaporite Member. Unfortunately, the absence of correlatable cycles within the Muschelkalk Halite Member (see section 17.8) precludes confirmation of this. The thinning of the Member towards the north-west, beyond the halite margin, presumably reflects the Member passing laterally into the mudstones of the Muschelkalk Mudstone Member (as seen by the uncertain upper boundary in the 'Staithes-20' reference well, encl. Well B).

Correlation of the Member with the outcrops around Nottingham (Chapter 4), indicates that the continued thickening of the Member towards this area, is related to an influx of coarser clastics ('skerries') into the basin from the south and south-west.

18.8 Subdivision

The Member is not subdivided.

18.9 Correlation (encl. Map 15)

An equivalent dolomitic/anhydritic unit forms the lower part of the Muschelkalk Claystone Member of NAM/RGD (1980) in the Northern and Southern Dutch Sectors. It has a similar thickness range to that of the U.K. Sector. Further east, particularly east of the Texel-Ijsselmeer High, the Member equates with the lower part of the Middle Muschelkalk Marl Member (*op. cit.*). It is, however, practically indistinguishable on logs from the rest of this Member. This is also the case in north Germany, where the Member equates with the lower part of the Mittlerer Muschelkalk Dolomit-Mergel-Serie of Wolburg (1969), and in East Germany where it equates with the lower part of the Oberer Dolomit-Mergel of the Anhydrit Folge of Docter *et al.* (1980).

An equivalent dolomite/anhydrite horizon is present above the Muschelkalk Halite Member in the Danish Central Graben (well U-1 of Michelsen and Andersen (1983)). Outside the Graben, the Members equivalent has not been recognised in the wells presented by Bertelsen (1980).

In the absence of the Muschelkalk Halite in the Polish area, the Member presumably correlates with (at least part of) the Middle Muschelkalk Dolomite Horizon of Senowiczowa (1961).

At outcrop in eastern England, the Member is tentatively correlated with the Carlton Formation of Warrington *et al.* (1980), as discussed in Chapter 4.

19. MUSCHELKALK MUDSTONE MEMBER (Dowsing Dolomitic Formation-New Member)

19.1 Type Well 48/12-1 (encl. Well A)

Depths: 3734' - 3922'

Thickness: 57.3 metres

19.2 Reference Well Staithes-20 (encl. Well B)

Depths: 1582' - 1703'

Thickness: 36.9 metres

19.3 Definition

A mudstone dominated sequence, anhydritic and occasionally dolomitic, with rare thin dolomite interbeds.

19.4 Remarks

As in part of the Dutch area, the boundary between the Middle Muschelkalk and the Upper Muschelkalk cannot be identified in the U.K. Southern North Sea area. Hence the sequence between the top of the Muschelkalk Evaporite Member and the top of the Dowsing Dolomitic Formation is here proposed as a single Member. The name, the Muschelkalk Mudstone Member, is adapted from a similar Dutch unit, the Muschelkalk Claystone Member (NAM/RGD 1980).

The Member is present in both the Dowsing Dolomitic Formation of the U.K. Southern North Sea, and in the proposed Dowsing Dolomitic Formation of the Mercia Mudstone Group of the subsurface eastern England.

19.5 Log Profiles and Lithologies

The gamma-ray and sonic logs exhibit serrated profiles, with the log values generally higher than those of the underlying Muschelkalk Evaporite Member. The sonic log, particularly, shows a highly serrated profile, which may in part be due to cycle skipping (e.g. type well 48/12-1, encl. Well A). Even when this is not obviously the case, the sonic log values are, in general, higher in this Member than in any other Member of the Dowsing Dolomitic Formation (e.g. wells 42/28-2 and 53/4-4, encl. Wells G and D respectively). The FDC/SNP overlays (e.g. encl. Well D) show a similar serrated profile, with high LPU values and a negative separation.

The log responses are typical of mudstones, an interpretation supported by the cuttings logs of encl. Wells G and H. The percentage of dolomite and anhydrite is generally around 5% (maximum 20%) and the cuttings are dominated by red-brown mudstones (probably representing both in situ and caved lithologies).

The generally high sonic log values are indicative of purer mudstones than those of the Röt Mudstone Members. Cycle skipping, due to very poor borehole conditions, is further evidence that this Member is much softer (and more prone to caving) than the mudstones in the Members below. The reason for this is seen in the 'Staithes-20' reference well core (encl. Well B). The mudstones are generally much less dolomitic than those below, and as a result are less indurated. This is reflected in the rubbly appearance of the core. Thin (up to 10 cm) dolomite horizons do occasionally occur, but in general the serrated log responses are a result of local concentrations of anhydritic/silty horizons.

19.6 Boundaries

19.6.1 Lower

This is everywhere the top of the Muschelkalk Evaporite Member (see section 18.6.2)

19.6.2 Upper

The top of this Member is the top of the Dowsing Dolomitic Formation. The boundary used is hence that proposed by Rhys (1975) for the Triassic type well 49/21-2 (fig. 3.2). Compared with the boundaries here proposed for the Members within the Dowsing Dolomitic Formation, this upper boundary of the Formation is particularly difficult to identify.

As proposed by Rhys (*op. cit.*), the boundary in the Triassic type well occurs at the base of a 15-metre zone of particularly high Δt values which Brennand (1975) referred to as 'a sonic log marker indicative of a regionally transgressive clay'. This marker is not easily recognised in individual wells, and hence detailed well-to-well correlation is usually required to position the boundary. The results of this correlation confirm the presence of the 'sonic log marker' in the majority of U.K. Sector wells, as can be seen from wells as far apart as the type well 48/12-1 (encl. Well A) and well 53/12-3 (encl. Well F). Both wells show a zone of generally higher, less variable Δt values immediately above the contact.

This 'sonic log marker' can be correlated into the Dutch Sector (e.g. well K/13-1, encl. Well K), where it immediately overlies the top of the Dutch Muschelkalk Formation of NAM/RGD (1980). This upper boundary has, in turn, been lithostratigraphically correlated with the top of the

Germanic Muschelkalk (*op. cit.*), as shown on fig. 6.10. Hence the top of the Dowsing Dolomitic Formation in the U.K. Southern North Sea area, equates lithostratigraphically with the top of the Muschelkalk in the basin centre.

The upper boundary of the Muschelkalk Mudstone Member is not recognisable in the 'Staithes-20' well core (encl. Well B). Lateral petrophysical log correlation from wells further into the basin tentatively suggest that it occurs at the top of a particularly anhydritic mudstone unit (Plate 3.24). The 'sonic log marker' is not, however, identified.

19.7 Thickness and Lateral Distribution (encl. Map 16)

The Member is everywhere present in the U.K. Southern North Sea area, and varies in thickness between 36 and 64 metres. On the East Midlands Shelf, across the northern part of the Anglo-Dutch Basin, and in the U.K Broad Fourteens Basin area, the Member is generally less than 50 metres thick. Greater thicknesses are restricted to the area immediately to the north-east of the Dowsing Fault Zone and the southern part of Quadrant 49.

The isopachs show no evidence of a margin against the Mid-North Sea High and the Cleaver Bank High.

19.8 Subdivision

The Member is not subdivided

19.9 Correlation (encl. Map 16)

As noted in section 19.6.2, the top of the Member coincides lithostratigraphically with the top of the Muschelkalk in the basin centre.

The Member equates with the majority of the Muschelkalk Claystone Member of the Dutch nomenclature (NAM/RGD 1980), although the latter also has at its base the equivalents of the Muschelkalk Evaporite Member. Further to the east in the Dutch area, as the carbonate content increases, it equates with the combined Middle Muschelkalk Marl and Upper Muschelkalk Members (*op. cit.*).

In north Germany, the lithostratigraphic equivalents of the Muschelkalk Mudstone Member are the upper part of the Mittlerer Muschelkalk Dolomite-Mergel-Serie plus the Oberer Muschelkalk (Trochiten-kalk and Ceratitenschichten) of Wolburg (1969). Similarly, in East Germany, the Member equates with the upper part of the Oberer Dolomit-Mergel of the Anhydrit-Folge and the Hauptmuschelkalk (Trochitenkalk and Tonplatten) of Dockter *et al.* (1980).

In the Danish area, the Member equates with the uppermost part of the Falster Formation of Bertelsen (1980), while in Poland, it presumably equates with the combined Middle Muschelkalk Super-Dolomite horizon and the Upper Muschelkalk of Senkowiczowa (1961).

In eastern England, the Member equates with the lower part of the Harlequin Formation of Warrington *et al.* (1980).

20. LITHOSTRATIGRAPHY v. BIOSTRATIGRAPHY

Fig. 3.19 summarises the published biostratigraphical data for the Dowsing Dolomitic Formation and its lithostratigraphic equivalents across the study area, excluding the most marginal area around Nottingham (see Chapter 4). No new studies have been undertaken by the present author.

The proposed lithostratigraphic units closely parallel the biostratigraphic zones, and there is no evidence for diachronism across the basin. The Skythian-Anisian boundary occurs at (or close to) the Röt/ Muschelkalk boundary, and the Anisian-Ladinian boundary occurs at the top of the Muschelkalk Evaporite Member. The three biostratigraphic markers proposed by Geiger and Hopping (1968), occur respectively at the top of the Muschelkalk Dolomitic Member, the top of the Muschelkalk Evaporite Member and within the Lower Keuper (Dudgeon Saliferous Formation), throughout the area.

The 'so-called' latest Skythian floras of the Germanic Basin may in fact equate with the early Anisian faunas of the Alpine Tethys type area (Kozur 1974, Visscher 1974). The uppermost Röt would hence be Anisian in age (Docter *et al.* 1980, Doubinger and Bühmann 1981, Gall *et al.* 1977). As this would be the case throughout the basin, it does not alter the time parallel lithostratigraphy.

CHAPTER 4

CHAPTER 4

CORRELATION OF THE MIDDLE TRIASSIC OUTCROP SUCCESSION OF NOTTINGHAMSHIRE (EASTERN ENGLAND) WITH THE SUBSURFACE DOWSING DOLOMITIC FORMATION

> 'A gamma-ray scan is an absolutely essential activity in the study of cores and outcrops, because virtually every good sedimentologic study of outcrops requires integration with subsurface geology. Moreover, the gamma-ray scan, better than anything else, facilitates direct comparison to the gamma-ray wire-line logs of the subsurface.'
>
> Potter *et al.* (1980), p.97

1. INTRODUCTION

Detailed correlation of the middle Triassic outcrop litho-stratigraphy of eastern England with that of the basin centre has not previously been possible. Firstly, prior to this thesis, no detailed subdivision of the Dowsing Dolomitic Formation existed east of the Dutch Sector (NAM/RGD 1980), and no subdivision whatsoever existed in the subsurface of eastern England with which to make such a correlation. Hence only the broadest of correlations with the north German succession have previously been proposed. Secondly, the Nottingham area lies in a very marginal position with respect to the Germanic Basin (encl. Map 1) and correlation with the basin centre is not obvious. The dolomites and thick halites which allow the lithostratigraphic subdivision in the subsurface are absent, and the succession is dominated by monotonous red (and occasionally green) mudstones, silty dolomitic mudstones, thin siltstones and occasional fine sandstones.

Even though the newly proposed subsurface lithostratigraphy has now been traced close to the outcrops, a direct correlation with the surface lithostratigraphy is not possible, as the former is based on

petrophysical log profiles, while the latter is based on sedimentology. In order to overcome this problem, this chapter describes how a surface gamma-ray profile, measured at outcrop, was used as a link between the surface and subsurface lithostratigraphies.

1.1 Outcrop Lithostratigraphy

The outcrop lithostratigraphy of the Mercia Mudstone Group in the Nottingham area, proposed by Elliott (1961) and amended by Warrington *et al.* (1980), is shown on fig. 4.1. Elliott (*op. cit.*) subdivided the essentially monotonous mudstone sequence into Formations, based on sedimentary structures and the recognition of thin (1 to 1.5 metre thick), coarse siltstone to very fine sandstone horizons (termed 'skerries'). The coarser units die out basinwards, and hence the litho-stratigraphic subdivision has only been applied over an area of about 24 km around Nottingham. Towards the north and east (i.e. into the basin), the Formations become increasingly difficult to determine.

The Mercia Mudstone Group is informally divided into the Mercia Mudstone *sensu lato* (*s.l.*) and *sensu stricto* (*s.s.*). The former refers to the entire sequence from the top of the Sherwood Sandstone Group to the base of the Penarth Group, while the latter excludes the sandy basal Woodthorpe and Colwick Formations (fig. 4.1). A similar subdivision into the Keuper Marl Group and 'Keuper Marl' was used by Warrington (1968). The Formations defined at outcrop around Nottingham are here referred to as the 'Nottingham lithostratigraphy'.

1.2 Previous Workers

All but the earliest authors (e.g. Hull 1869) equate the lower Mercia Mudstone *s.l.* in part with the middle Triassic, but they vary on the detailed relationship between the Nottingham and Germanic lithostratigraphies. None, except the present interpretation and that of Balchin and Ridd (1970), are based on petrophysical logs. All the other interpretations, based on lithological and palaeontological data, universally place the top of the Muschelkalk (i.e. the top of the Dowsing Dolomitic Formation) at the Colwick/Radcliffe Formation boundary, and hence the Mercia Mudstone *s.s.* is equated with the Germanic Keuper (fig. 4.2). These authors disagree as to whether the Upper Bunter (i.e. Röt) is represented by the Woodthorpe Formation (Audley-Charles 1970, Geiger and Hopping 1968), or is not present due to a base Mercia Mudstone unconformity (Ager 1970, fig. 3 of Warrington 1970a). The Colwick Formation has also been interpreted as representing the very limit of the Muschelkalk sea transgression, from the discovery of the brackish to intertidal *Lingula tenuissima* **Bronn** (Rose and Kent 1955).

Geiger and Hopping (1968) was the first paper to present a subsurface palynological correlation from north Germany to the Yorkshire coast. Their correlation to the Nottingham outcrops was, however, based on the palynological data of Clarke (1965) for the Worcester Basin, where the Röt was equated with the Woodthorpe Formation, and the top Muschelkalk was placed at the top Colwick Formation (fig. 4.2).

Balchin and Ridd (1970) were the first authors to provide a detailed subsurface log correlation of the Mercia Mudstone Group across eastern England. Their correlation to the Germanic lithostratigraphy is, however, incorrect in detail, as the top and base of the Muschelkalk

equivalent are taken from the incorrectly picked boundaries of Geiger and Hopping (1968) for the 'Tetney Lock' well. The basis for their correlation between the Nottingham and subsurface lithostratigraphies is unclear, as none of the wells used was cored (Balchin and Ridd *op. cit.*). This paper is, however, important because for the first time, part of the Mercia Mudstone *s.s.* (i.e. the Radcliffe and lower Carlton Formations) was equated with the Germanic Muschelkalk.

In order to resolve the various conflicting correlations between the Nottingham and Germanic lithostratigraphies, a surface gamma-ray profile was measured in the middle Triassic succession at Kirton Brickworks, Nottinghamshire. This was then linked with both the surface and subsurface lithostratigraphies.

2. THE SURFACE GAMMA-RAY PROFILE

2.1 Kirton Brickworks (G.R. SK693682)

In choosing a location to measure a surface gamma-ray profile two main factors were considered important. Firstly, a long continuous section was necessary in order to produce a sufficiently long profile to compare with the subsurface logs. Secondly, the marginal Nottingham lithostratigraphy had to be recognisable at the outcrop, which also had to be sufficiently basinal to produce a gamma-ray profile comparable with that of the subsurface logs.

Kirton Brickworks, lying 26 km to the north of Nottingham, was chosen to attempt the gamma-ray profile because it is one of the largest exposures in the lower part of the Mercia Mudstone *s.l.* in eastern England. In 1983, a 38-metre section was accessible out of a total

exposure of about 49 metres. The quarry also lies between the thicker, more basinal deposits of the East Midlands Shelf to the north and east, and the thinner, more marginal deposits of the Nottingham area to the south (fig. 4.3). It lies 19 km south-west of the nearest available basinal well (Torksey-4) and 24 km north of the marginal outcrops and wells around Nottingham.

Kirton is the most northerly exposure for which the Nottingham lithostratigraphy has been proposed. Farther to the north, in the more basinal East Retford area, it was considered impossible to recognise these Formations (Smith *et al.* 1973, Warrington 1970a). At Kirton, the Nottingham lithostratigraphy has been variously interpreted by Edwards (1967), Elliott (1966) and Warrington (1968). For this reason, it was necessary to relog the quarry lithologically to determine the correct Nottingham lithostratigraphy, as well as measuring a gamma-ray profile to correlate with the subsurface lithostratigraphy.

2.2 Surface Gamma-ray Profiles - Previous Work

Despite the quote at the start of this chapter, very little has been published on outcrop gamma-ray profiles in sedimentary sequences. The earliest surface gamma-ray surveys were undertaken, usually in igneous terrain, to explore for radioactive minerals (reviewed in Doig 1968). Løvborg *et al.* (1972), working on igneous drill-core, were the first authors to show that a gamma-ray profile measured along the surface of the core was comparable with the down-the-hole gamma-ray survey of the same borehole.

In the early work on sedimentary sequences (reviewed in Lucas 1971) no attempt was made to link the surface profiles into the

subsurface. More recent studies (Chamberlain 1984) have concentrated on the use of gamma-ray profiles for reconnaissance in little-known areas.

This present work was mainly inspired by the paper of Provo *et al.* (1978), in which a surface gamma-ray profile was linked into a basinwide subsurface study. The results showed that a green shale horizon, within the Upper Devonian black shales of Kentucky, could be correlated from outcrop into the subsurface to produce a basinwide gamma-ray marker.

2.3 Method and Result Validity

Nowhere in the literature is the method for obtaining an outcrop gamma-ray profile adequately described. For this reason, the method devised, and the resulting data validity are discussed briefly below, and considered in detail in Appendix B.

The quarry was logged lithologically, and then gamma-ray readings were taken up the succession every 1/3 metre. The background gamma-ray count was noted, and a radioactive source (a Standard) was frequently measured to indicate any changes in instrument sensitivity.

The resulting profiles are plotted on fig. 4.4. Column 1 shows the litho-log of the sequence. In column 2 the measured gamma-ray field data profile (and the average background count) is shown along with the statistical error bars. Column 3 shows the drift in the instrument sensitivity (i.e. the Standard measurement) and column 4 shows the field data profile amended for this instrument drift. As discussed in Appendix B, the 'corrected' data profile in column 4 closely resembles the field data profile indicating that the major variations up the profile are not the result of instrument error. Similarly, the larger gamma-ray peaks in

column 2 fall outside the range of statistical error. It is hence concluded that the measured gamma-ray variation reflects true variation up the section. The gamma-ray/lithology relationship discussed below supports this.

2.4 Gamma-ray/Lithology Relationships

In almost all cases, high gamma-ray counts are associated with zones containing green or purple-green mudstone (fig. 4.4). A possible explanation for this relationship is that uranium is associated with organic matter. This in turn is more likely to be preserved in green rather than red mudstones.

Colour in mudstones grades from green to purple to red with an increase in the Fe^{3+}/Fe^{2+} ratio (i.e. an increase in oxidation), and from green to grey to black with an increase in the percentage of organic matter (Potter *et al.* 1980, p. 55). Oxidation is inhibited by the presence of organic matter, but the preservation potential of organic matter under oxidising conditions is low. Hence red mudstones contain less organic matter than green mudstones (which in turn contain less than black mudstones). This relationship has been reported in the middle Triassic, where organic-walled palynomorphs are preserved in the green mudstone horizons, but are absent from the red mudstones (Smith and Warrington 1971, Warrington 1970a, Visscher 1966).

The relationship between organic matter and uranium content has been noted by several authors (reviewed in Rider 1986 p. 63). The Uranyl ion (UO_2^{2+}) is absorbed by organic matter, resulting in the frequent association between high gamma-ray log values and organic-rich ('hot') shales (*op. cit.*). Green mudstones should therefore have a higher gamma-

ray count than red mudstones and a lower count than black mudstones.

Although this relationship with organic matter has not been proven at Kirton, the green mudstones do show a higher gamma-ray count than the interbedded red mudstones. Similarly, Provo *et al.* (1978) found that interbedded green shales in an organic-rich black shale sequence showed the lower gamma-ray values.

At Kirton there is also a possible relationship between gamma-ray count and grain-size. In general mudstones tend to have much higher gamma-ray counts than sandstones, and admixtures of the two result in intermediate values (Schlumberger 1972a, p.55). At Kirton, the gamma-ray values in the central part of the profile are lower than those in the upper and lower zones, perhaps reflecting the silty nature of this part of the sequence, as well as the dearth of green interbeds (fig. 4.4).

Hence, both statistically and by comparison with lithology, the Kirton gamma-ray profile appears valid, and therefore an attempt to correlate this into the subsurface is justified.

3. CORRELATION INTO THE SUBSURFACE

3.1 Details of the Kirton Profile

To aid correlation, the gamma-ray profile is divided into three zones (fig. 4.4). These are, from the base up, a zone of moderate to high gamma-ray values (Zone 1), a zone of less variable, and generally lower gamma-ray values (Zone 2), and a zone of alternating high and low gamma-ray values (Zone 3).

In Zone 1 (Plates 4.1 and 4.2), the high gamma-ray values are closely related to the green and purple-green mudstones and siltstones.

The top of the Zone is taken immediately above the last distinctive gamma-ray peak in this part of the profile, which coincides lithologically with a change from red mudstones with interbedded green and purple-green mudstones and siltstones, to red mudstones with interbedded red-brown siltstones.

Gamma-ray values in Zone 2 are generally lower than those in Zones 1 and 3, due possibly to the large number of thin, impersistent, coarse siltstone to fine sandstone horizons, and the general lack of green interbeds (upper part of Plate 4.2). The top of the Zone is taken as the base of a major gamma-ray peak which coincides with the first of several thick green interbeds.

Zone 3 (Plate 4.3) is characterised by alternating high and low gamma-ray values, due to these green mudstone and siltstone interbeds. Four such green horizons are accessible, and each has an associated high gamma-ray count. Inaccessible green beds higher in the quarry face presumably also have high gamma-ray values, and on the basis of this, the field data profile on fig. 4.4 has been extended beyond the top of the measured section, to the top of the quarry.

3.2 Correlation with the 'Torksey-4' Well

Although 49 metres of the Mercia Mudstone *s.l.* are exposed at Kirton Brickworks, this is nonetheless a relatively short profile to attempt to correlate with the subsurface. To aid correlation, the thickness of the Mercia Mudstone *s.l.* below the base of the Kirton succession, has been estimated. Edwards (1967, p. 136) reported this as 80 feet (24 metres), but based on structural contours on the base of the Mercia Mudstone Group (fig. 4.5), this has been reassessed at about 36

metres. From this it was predicted that the base of the Kirton profile would correlate with an horizon approximately 36 metres above the base of the Mercia Mudstone Group in the 'Torksey-4' well.

The best-fit correlation between the Kirton profile and the 'Torksey-4' well does in fact occur very close to this predicted position (fig. 4.6). In general the fit between the profile and the log is considered good (despite the latter being run in casing). The most conclusive correlation is in Zone 3 and the upper part of Zone 2, where practically a peak-by-peak match is possible. A slightly more tentative correlation can also be made in Zone 1. As expected, the Kirton profile correlates with a slightly thicker sequence in the more basinal 'Torksey-4' well (fig. 4.6).

The main difference between the Kirton profile and the 'Torksey-4' log occurs in Zone 2. At Kirton, the Zone 2 gamma-ray values are generally lower than those in Zones 1 and 3, whereas this is not the case in the 'Torksey-4' well. This difference may reflect the absence of coarser siltstones and fine sandstones in the more basinal 'Torksey-4' well.

The correlation between the Kirton profile and the 'Torksey-4' well is as good as that which would be accepted for a well-to-well correlation. A similar good correlation occurs at this same horizon in the 'Axholm', 'Glentworth' and 'Bardney' wells, and a fair correlation occurs in the 'Nettleton' and 'Nocton' wells. The correlation with the 'Bardney well' is shown on fig. 4.7.

3.3 The Subsurface Lithostratigraphy at Kirton

Fig. 4.8 shows the gamma-ray correlation along the line of

section shown on fig. 4.3, running north-east/south-west towards the basin margin, and including the 'Torksey-4' well and the Kirton outcrop. The selected datum line, recognised in all of the wells, is the top of the Muschelkalk Dolomitic Member (i.e. the top of the 'gamma-ray marker' of Balchin and Ridd (1970)). Below this horizon, the top of the Main Röt Mudstone Member and the Main Röt Evaporite Member can be traced with certainty to the 'Torksey-4' well.

Based on this correlation, the Kirton outcrop can be linked into the subsurface lithostratigraphy. Zones 1 and 2 lie within the Main Röt Mudstone Member, and Zone 3 within the Muschelkalk Dolomitic Member. The boundary between the Röt and Muschelkalk successions almost exactly equates with the top of Zone 2 (fig. 4.6).

4. THE NOTTINGHAM LITHOSTRATIGRAPHY AT KIRTON

4.1 Previous Work

Previous workers have not been in agreement as to the position of Kirton within the Nottingham lithostratigraphy. Edwards (1967) interpreted the entire sequence as Colwick Formation, with the uppermost beds possibly Mercia Mudstone *s.s.*, while Elliott (1966) and Warrington (1968) recognised the uppermost Colwick to lower Harlequin Formations in the quarry. In the latter interpretation, the top of the Colwick Formation was placed 2.4 metres below the lowest purple-green horizon (i.e. at the base of the quarry in 1983), and the Radcliffe and Carlton Formations were both estimated at 17 metres thick (*op. cit.* p. 144, p. 151 and p. 156). The proposed Formations are shown on fig. 4.9.

In proposing the lithostratigraphic subdivision for the quarry,

Warrington noted that the lithologies present were in many ways atypical of the Formations as developed in the type area around Nottingham. For example, the Radcliffe Formation contained "...a prominent horizon of micaceous, mudcracked green and purple mudstone and siltstone, which is not represented further south." (*op. cit.*, p. 151), and, in the Carlton Formation "...sandstone bands up to 6 inches thick are fairly common and are atypical of the Formation near Nottingham." (*op. cit.*, p. 156).

4.2 This Study

The quarry was re-examined sedimentologically, and Warrington's (1968) interpretation of the surface lithostratigraphy is now disputed. By comparison with the described sedimentology of the type area (Elliott 1961), a new interpretation, bearing closer resemblance to that of Edwards (1967), is presented (fig. 4.9). In this interpretation, Zones 1 and 2 are equated with the Colwick Formation, and Zone 3 with the Radcliffe Formation.

Around Nottingham, the boundary between the Colwick and the Radcliffe Formations separates an underlying quartzose sequence, characterised by current deposition, from an overlying finer evaporitic sequence (Elliott 1961). Such a boundary at Kirton occurs at the top of Zone 2, with frequent, thin, cross-laminated, ripple-marked (and occasionally scour-based) siltstones and fine sandstones below, and frequent pseudomorphs after halite above (fig. 4.10). The boundary underlies a pale green coloured 'skerry' sandstone, similar to that reported in the Nottingham area (Elliott *op. cit.*).

At Kirton, the most distinctive feature of Zone 3 is the interbedding of up to 1 metre thick green horizons with the red

mudstones. According to Elliott (fig. 2 of 1961), this mainly occurs in the upper Colwick and upper Carlton Formations. It has, however, also been observed in the Radcliffe Formation at its type locality near Nottingham (fig. 4.10 inset), where the Formation's development, including halite pseudomorphs, is similar to that seen in Zone 3 at Kirton.

It is hence proposed that Zones 1 and 2 equate with the Colwick Formation, and Zone 3 with the Radcliffe Formation.

5. REGIONAL CORRELATION OF THE SURFACE AND SUBSURFACE LITHOSTRATIGRAPHIES

By comparing the surface and subsurface correlations at Kirton, it is evident that the exposed Colwick Formation equates with the upper part of the Main Röt Mudstone Member, and the exposed Radcliffe Formation equates with the lower part of the Muschelkalk Dolomitic Member (fig. 4.9). This has implications for the regional stratigraphy of eastern England.

5.1 Colwick Formation/Main Röt Mudstone Member

The Main Röt Mudstone Member (and its equivalent the Colwick Formation) thickens from the marginal area south of Kirton, to a fairly constant 52 to 55 metres across the East Midlands Shelf north-east of Kirton (fig. 4.12).

This is in direct contrast to the thinning of the Colwick Formation in that direction reported by Smith *et al.* (1973) for the area to the north of Kirton. The contradiction occurs because basinwards, progressively lower beds of the sandy Colwick Formation pass laterally into previously undifferentiated Mercia Mudstone *s.s.* until the northern

limit (shown on fig. 4.3) is reached (Smith and Warrington 1971). It is evident from fig. 4.8 that, although the Colwick Formation *s.s.* thins towards the north and east, its lateral equivalent the Main Röt Mudstone Member, thickens slightly in that direction.

As the base of the Radcliffe Formation equates with the base of the Muschelkalk Dolomitic Member, northwards from Kirton an increasing thickness of undifferentiated Mercia Mudstone (equivalent to the Main Röt Mudstone Member) must lie between the recognised top of the Colwick Formation and the base of the Radcliffe Formation. The failure of previous authors to recognise this fact may explain why the Nottingham lithostratigraphy could not be applied north of Kirton (Smith *et al.* 1973, Warrington 1970a). A new Formation will have to be defined at outcrop if the Nottingham lithostratigraphy is to be extended to this area.

This also explains the difference between the proposed Nottingham lithostratigraphy at Kirton and the work of Elliott (1966) and Warrington (1968). The present base of the quarry is so positioned because the sequence becomes increasingly sandy below this level (pers. comm. E. Battey, Assist. Manager Kirton Brickworks). If the top of this more sandy development is chosen as the top of the Colwick Formation (Elliott *op. cit.*, Warrington *op. cit.*), then the sequence in the quarry below the Radcliffe Formation (Zone 3) must represent a transitional facies laterally equivalent to the Colwick Formation to the south and the finer Main Röt Mudstone Member to the north. (It cannot strictly be called the Main Röt Mudstone Member at Kirton, as the sequence is probably more sandy than the Member in the 'Torksey-4' well (section 3.2).) In the present interpretation, this so-called 'transitional facies' is included in the Colwick Formation, which hence is directly

overlain by the Radcliffe Formation (fig. 4.11).

The above authors (*op. cit.*) failed to recognise that, based on their interpretation, the Radcliffe Formation does not directly overlie the Colwick Formation. This resulted in the reported atypically developed lithologies in the Formations they identified in the quarry (section 4.1).

Close to the margin around Nottingham, there is some evidence from the literature that the upper beds of the Colwick Formation pass laterally northwards into the lower part of the Radcliffe Formation. Firstly, Elliott (1961) reports both green beds near the top of the Colwick Formation around Nottingham, and Colwick-type facies in the lower Radcliffe Formation at its type locality (in the same area). Secondly, in this more marginal area, the Colwick Formation appears to thicken directly at the expense of the Radcliffe Formation (fig. 4.12).

The Colwick Formation is hence diachronous with respect to the subsurface lithostratigraphy, equating only with the lower part of the Main Röt Mudstone Member north of Kirton, with (probably) the whole of the Member at Kirton, and possibly interdigitating with the lowermost Radcliffe Formation (Muschelkalk Dolomitic Member equivalent) around Nottingham (fig. 4.11).

5.2 Higher Formations

The sequence above the lowermost Radcliffe Formation is not exposed at Kirton, and hence the gamma-ray response of the Formations above this level are unknown. However, the relationship between gamma-ray and lithology established at Kirton (section 2.4) can be used in conjunction with the described lithologies (Elliott 1961) to estimate the

boundaries of the higher Formations on the subsurface logs.

5.2.1 Radcliffe Formation/Muschelkalk Dolomitic Member

The most distinctive feature of the Radcliffe Formation at Kirton, is the correlation between alternating high and low gamma-ray values, and lithology. In the 'Torksey-4' well (fig. 4.6), a zone of alternating gamma-ray values extends (beyond the region correlated with Kirton) to the base of the 'gamma-ray marker' of Balchin and Ridd (1970), and is hence considered to equate with the Radcliffe Formation. At Dorket Head Brickpit, north of Nottingham (G.R. SK591474), appreciable green beds occur in the uppermost part of the Radcliffe Formation (Elliott 1961). Such an horizon could result in the high gamma-ray values of the 'gamma-ray marker', which would then occur at the very top of the Radcliffe Formation.

This interpretation implies that the Radcliffe Formation is appreciably thicker in the basin than at the margin (fig. 4.12) but, as explained in section 5.1, this is in part a result of the interdigitation of the lower part of the Formation with the Colwick Formation close to the basin margin. The Radcliffe Formation hence equates with the Muschelkalk Dolomitic Member, everywhere except near to the basin margin, where the latter in part equates with the Colwick Formation.

5.2.2 Carlton Formation/Muschelkalk Evaporite Member

By equating the Radcliffe Formation with the Muschelkalk Dolomitic Member, the Carlton Formation must, in part, equate with the Muschelkalk Evaporite Member. Around Nottingham, the lower Carlton Formation (12 metres thick) is characterised by massive, poorly bedded mudstones and siltstones, while the upper Carlton Formation (9 metres

thick) contains alternations of thick green beds, siltstones and mudstones (including the distinctive dolomitic Plains Skerry), which allow a bed-by-bed correlation at outcrop over about 19 km (Elliott 1961). It is not possible to relate this description to the cased 'Torksey-4' well, but it can be identified in the 'Glentworth' and 'Bardney' wells. In the latter well (fig. 4.7), the high values of the 'gamma-ray marker' are overlain by 10 metres of fairly constant values (lower Carlton Formation), followed by an 11 metre zone of highly variable values (upper Carlton Formation). The Formation has a similar thickness to that in the Nottingham area (Elliott 1961). So defined, the Formation equates exactly with the Muschelkalk Evaporite Member of the subsurface lithostratigraphy, and hence the dolomitic/anhydritic mudstones of the U.K. Southern North Sea area are represented at outcrop in part by the highly dolomitic Plains Skerry.

5.2.3 Clareborough Formation

Lying within the Mercia Mudstone *s.s.* to the north of Kirton, is the Clareborough Formation (Warrington *et al.* 1980). This is a distinctive 3 to 12 metre thick skerry-belt composed of gypsiferous mudstones and dolomitic siltstones and sandstones (Warrington 1974). Its relation to the Nottingham lithostratigraphy is uncertain, and it has variously been equated with the 'gamma-ray marker' (i.e. at the top of the Radcliffe Formation), and with the East Bridgeford Gypsum (of Firman 1964), which probably occurs near the Carlton/Harlequin Formation boundary (Smith and Warrington 1971).

The Clareborough Formation occurs about 100 metres above the Sherwood Sandstone Group at Tuxford, 5 km north-east of Kirton (Smith and Warrington *op. cit.*). Based on the near constant thickness of the litho-

stratigraphic units across eastern England, the Formation would hence occur at about the top of the 'gamma-ray marker'. It is suggested here however, that it probably occurs slightly higher, and hence equates with the similarly dolomitic Plains Skerry of the upper Carlton Formation, and therefore with the Muschelkalk Evaporite Member of the subsurface (fig. 4.11).

5.2.4 Harlequin Formation/Muschelkalk Mudstone Member

The average thickness of the Harlequin Formation is 46 metres (Elliott 1961), which exceeds the thickness of the Muschelkalk Mudstone Member in the Nottinghamshire area (encl. Map 16). As a result, the top of this Formation and the higher Formations of the Mercia Mudstone Group (the Edwalton, Trent and Parva Formations) do not lie within the Dowsing Dolomitic Formation and hence are not considered further.

6. PALYNOLOGY

6.1 Eastern England

No new palynological work has been undertaken, but an attempt is made to relate the published work to the lithostratigraphy presented above. It is mainly the distinctive basal Formations of the Mercia Mudstone *s.l.* that have been dated. Around Nottingham these are the Woodthorpe and Colwick Formations, and further north the Retford Formation (basinal equivalent of the Woodthorpe Formation).

As noted in Chapter 3 section 20, the Members of the Dowsing Dolomitic Formation are not diachronous across the majority of the basin. Indeed, in the 'Tetney Lock' well near the east coast of England, a late

Skythian assemblage equates with the Main Röt Mudstone Member and an Anisian assemblage with the Muschelkalk Dolomitic Member, as in the Germanic area (Geiger and Hopping 1968).

Across most of eastern England, there is similarly no evidence of the units being diachronous. The Retford Formation (equivalent of the Main Röt Evaporite Member) has been dated as late Skythian as far south as the Markham Clinton borehole, 5 km north of Kirton (Smith and Warrington 1971). However, south of this, in the Ompton borehole, 3 km south of Kirton (G.R. SK677648), this Formation has been dated as early Anisian (Smith and Warrington *op. cit.*). Around Nottingham, its marginal equivalent, the Woodthorpe Formation, has also been dated as Anisian (Warrington 1970b).

At Eakring, 6 km south of Kirton, the overlying Colwick Formation (equivalent of the late Skythian Main Röt Mudstone Member to the north-east) has been dated as early Anisian (Smith and Warrington 1971). A similar age has also been proposed for the Formation to the west of Nottingham (Frost and Smart 1979).

It is because the Colwick Formation has only been dated in these marginal areas, that previous authors have equated it solely with the Muschelkalk of north Germany. Around Nottingham, it does indeed equate with the Anisian Muschelkalk, but farther into the basin it equates with the late Skythian Röt succession.

The lower part of the Mercia Mudstone *s.l.* is hence diachronous to the south of Kirton, but this is a local feature near to the basin margin, and does not appear to be the case over most of eastern England. From the literature, it is unclear whether the Formations of the Mercia Mudstone *s.s.* are also diachronous. They do not appear to be so with respect to the subsurface lithostratigraphy (fig. 4.11).

6.2 Palynology at Kirton

Smith and Warrington (1971) obtained two late Ladinian assemblages from the succession at Kirton, the lower (sparse) assemblage from approximately 5 metres above the top of Zone 1, and the upper assemblage from the base of Zone 3.

This late Ladinian age for the Colwick Formation is difficult to reconcile with the regional palynology as it implies considerable diachronism of the Formation and conflicts with the older ages both to the north and south. The late Ladinian age of the upper assemblage is not impossible if the Anisian ages further south (Frost and Smart 1979, Smith and Warrington 1971) are from a lower part of the Formation. The possibility that the age determination at Kirton is incorrect must, however, also be considered.

7. REVIEW OF THE SURFACE/SUBSURFACE CORRELATION

There is a good fit between the Kirton gamma-ray profile and the subsurface logs (figs. 4.6, 4.7). The outcrop lithostratigraphy shows many similarities with the type area around Nottingham. As a result, the Colwick Formation is equated with the Main Röt Mudstone Member, and the Radcliffe Formation with the Muschelkalk Dolomitic Member. Based on the established gamma-ray/lithology relationships and the described lithology of the Formations, the top of the Radcliffe Formation is equated with the top of the Muschelkalk Dolomitic Member, and the top of the Carlton Formation with the top of the Muschelkalk Evaporite Member.

Close to the basin margin, the Colwick Formation interdigitates with the lowermost Radcliffe Formation, in the area where the Mercia

Mudstone isopachs indicate rapid thinning, and it is in this area that the regional palynology (Smith and Warrington 1971) indicates that the lower Formations become diachronous. The late Ladinian age at Kirton is, however, difficult to explain, requiring that the Colwick Formation is younger than at localities both to the north and south.

CHAPTER 5

CHAPTER 5

MIDDLE TRIASSIC STRUCTURAL DEVELOPMENT

1. INTRODUCTION

The general introduction to the structural development of the Germanic Basin was given in Chapter 1 section 1. In this present chapter, the middle Triassic structural development of the study area is considered in more detail from the thickness distribution of the various Members of the Dowsing Dolomitic Formation (and their lateral equivalents). In the main, this study confirms the general conclusions of the previous authors expressed in Chapter 1, although additional structural elements (e.g. the Broad Fourteens Basin) are also shown to have been active during the middle Triassic.

Depositional models for the various Members are discussed in Chapter 6; however, two features of relevance to the structural interpretation are introduced here. Firstly, all the Members are thought to have been deposited at or close to sea level and hence their thickness distribution closely reflects the differential structural movements within the basin during deposition. (Post-depositional compaction is not considered to greatly affect the general picture.) Secondly, the distribution of individual halite cycles within the Main Röt Halite Member is used to distinguish between depositional and post-depositional highs. The former are identified in those areas where some halite cycles extend beyond others, whereas the latter are inferred in those areas where the margins of all the halite cycles are coincident (a result of dissolution associated with uplift and nearby erosion). This difference is seen on encl. Map 11 by comparing the south-western depositional

margin of the halite basin in the U.K. Sector, with the essentially solution margin on both sides of the Cleaver Bank High. This is discussed further in Chapter 6 section 6.2.

2. STRUCTURAL ELEMENTS WITHIN THE STUDY AREA

The overall middle Triassic basin shape is best seen from the thickness distribution of the Main Röt Mudstone Member (encl. Map 13). This Member shows neither the lateral lithology changes of the Muschelkalk Dolomitic and Muschelkalk Mudstone Members, nor the post-Triassic dissolution effects of the Röt and Muschelkalk Halite Members. The overall basin shape is that of an east-west trending depression whose central axis approximately lies along latitude 54°N, from the U.K. Sector across to the Northwest German area. Superimposed on this inherited Permian Basin structure (Chapter 1 section 1.2) are the additional structural elements active during the middle Triassic.

To the west of the Texel-Ijsselmeer High, three major structural units show evidence of differential subsidence during the middle Triassic. From west to east these are the East Midlands Shelf, the Anglo-Dutch Basin and the Broad Fourteens Basin. To the east of the Texel-Ijsselmeer High, the limited well data available support middle Triassic differential movement on the Swells and Troughs of the southern basin margin, as noted in Chapter 1 section 1.5 (encl. Maps 2-16).

2.1 East Midlands Shelf

This extends eastwards from the Pennine High to the Dowsing Fault Zone (fig. 1.2), and is characterised by generally slow subsidence

compared with the basins further east. Throughout the middle Triassic, the thickness of the non-halitic Members varies little across the Shelf, with only a gradual thickening towards the north and east (encl. Maps 13, 14 and 16). The exception to this is the Lower Röt Mudstone Member (encl. Map 4), which directly overlies the Hardegsen unconformity in this area. The thickness of this Member is discussed further in Chapter 6 section 2.2.2.

Towards the north of the East Midlands Shelf, the halitic Members indicate the presence of an apparent sub-basin. These Members are absent across the East Midlands Shelf (except close to the Dowsing Fault Zone), but occur in an east-west trending area immediately to the north of 54° N (encl. Maps 5, 12 and 15). This embayment, which is most pronounced in the Main Röt Halite Member (encl. Map 5), closely coincides with the position of the Jurassic Cleveland Basin of Kent (1980).

Although a thick halite sequence is preserved in this area in the Main Röt Halite Member, it is unlikely that the present isopachs reflect differential subsidence during deposition. More probably halite was deposited over a larger part of the East Midlands Shelf but this has subsequently been removed by dissolution which post-dates the Jurassic subsidence in the Cleveland Basin. As a result, the deeper buried halite within this Basin was protected while that outside the Basin suffered dissolution (fig. 5.1). Several factors support this interpretation.

Firstly, none of the non-halitic Members show any appreciable thickening into the Cleveland Basin (encl. Maps 13, 14 and 16), yet differential subsidence should be reflected more in these slower deposited Members. Secondly, the margins of the individual Main Röt Halite Member cycles are all coincident in the area of the Cleveland Basin, implying a dissolution rather than a depositional margin to the

halite (encl. Map 11). Finally, the Main Röt Halite Member equivalent in the cored 'Staithes-20' well, immediately to the north of the Cleveland Basin, is a collapse breccia (encl. Well B). Post-Triassic dissolution has hence occurred in this area and a similar situation is also proposed for the area immediately to the south of the Cleveland Basin.

The Upper Röt Halite and Muschelkalk Halite Members do not extend as far to the west in the Cleveland Basin area as the Main Röt Halite Member (encl. Maps 12 and 15), but their margins too may in part be the result of post-Triassic dissolution. In the absence of correlatable halite cycles within these Members, this cannot be proved.

2.2 Anglo-Dutch Basin

This lies between the Dowsing Fault Zone and the structural lineament which is here proposed as the western margin of the Broad Fourteens Basin (fig. 1.2). Almost all the Members of the Dowsing Dolomitic Formation above the basal Lower Röt Mudstone Member show an appreciably thicker development in the Anglo-Dutch Basin compared with the East Midlands Shelf, indicating more rapid subsidence during deposition.

Within the Anglo-Dutch Basin, the Sole Pit Trough was an area of particularly rapid subsidence. This area occurs close to the Dowsing Fault Zone around 54° N, and is roughly defined by the 350 metre isopach on encl. Map 1. The majority of Members show a thicker than average development within the Sole Pit Trough (encl. Maps 4-16), and as a result, the maximum observed Dowsing Dolomitic Formation thickness, in the Anglo-Dutch Basin, occurs in this area (406 metres in well 47/5-1, encl. Map 1).

2.3 Broad Fourteens Basin

The north-west/south-east trending Broad Fourteens Basin (fig. 1.2) has been recognised as a Mesozoic structural element in the Southern Dutch Sector by several authors, none of whom extend the basin into the U.K. Sector (Blair 1975, Jenkins and Twombley 1980, Oele *et al.* 1981, Tubb *et al.* 1986 and Rhys 1975). An extension of this general structural trend into the U.K. Sector is, however, shown schematically by Gibbs (1986) and Glennie (1986). Evidence from the thickness distribution of the Dowsing Dolomitic Formation Members indicates that differential subsidence occurred in the Broad Fourteens Basin during part of the middle Triassic, and that an extension of this Basin existed in the north-eastern part of the U.K. Southern North Sea.

The proposed extension of the Broad Fourteens Basin into the U.K. Sector is based primarily on the distribution of the Solling Mudstone Member (encl. Map 2). In the Southern Dutch Sector this Member thins towards the south-west to a depositional margin which approximately coincides with the south-western edge of the Broad Fourteens Basin (fig. 5.2). A similar thinning towards a south-western margin in Quadrants 43 and 44 of the U.K. Sector implies an extension of the Broad Fourteens Basin into this area.

Further evidence that this margin occurs along a line of Triassic structural weakness comes from the underlying Bunter Sandstone Formation. Firstly, the thick sandstones typical of the U.K. Sector become increasingly argillaceous towards the north-east from this margin (figs. 3.5 and 3.8), and secondly, the gas discoveries in the Formation, both in the U.K. and Dutch Sectors, all lie close to the proposed basin margin, as shown on encl. Map 2 (reported in: Browns Geological

Information Services Bulletin, v.9 (pt. 1-4), v.11 (pt. 8/10/11/12), v.12 (pt. 8), v. 13 (pt. 2)). Although the gas accumulations may be salt-induced structures (Bifani 1986), this regional trend must reflect a deeper structural lineament.

Differential subsidence of the Broad Fourteens Basin with respect to the Anglo-Dutch Basin resulted in Solling Mudstone Member and Riff Sandstone Member deposition being restricted to the Broad Fourteens Basin (encl. Maps 2 and 3). The overlying Lower Röt Mudstone Member deposition (encl. Map 4) extended further west into the Anglo-Dutch Basin, but a considerably thicker sequence in the Broad Fourteens Basin (particularly in the U.K. Sector) indicates that differential subsidence between the two basins continued. This became less marked in the higher Members of the Dowsing Dolomitic Formation. In the Main Röt Halite Member, thickness variations indicate that differential subsidence was most pronounced in Cycle A (encl. Map 6) and less so in the overlying cycles (e.g. encl. Map 9). The Main Röt Mudstone Member and Muschelkalk Dolomitic Member possibly show a slightly thicker development in the Broad Fourteens Basin (encl. Maps 13 and 14), but the higher Members of the Dowsing Dolomitic Formation (encl. Maps 15 and 16) do not show any evidence for differential subsidence between this and the Anglo-Dutch Basin.

Hence active differential subsidence between the Broad Fourteens Basin and the Anglo-Dutch Basin was not continuous throughout the middle Triassic. It was most pronounced during Solling Mudstone, Riff Sandstone and Lower Röt Mudstone Member deposition, and decreased during the deposition of the higher Members of the Dowsing Dolomitic Formation as the two Basins increasingly acted as a single structural unit.

2.3.1 Basin Margin Offset

The isopachs of both the Solling Mudstone Member and the Riff Sandstone Member indicate an offset of the Broad Fourteens Basin margin in the Dutch Sector along a line trending north-east/south-west from Block L/2 to K/17 (encl. Maps 2 and 3). This offset occurs in an area where the post-Triassic Cleaver Bank and Texel-Ijsselmeer Highs almost meet and hence is partially obscured.

A post-depositional dextral wrench movement of some 40 km could have produced this offset, but this is considered unlikely, as the isopachs of those Members above the Riff Sandstone Member do not show any evidence of an offset (encl. Maps 4, 13, 14, 16). More likely is that the isopachs reflect a dog-leg in the Broad Fourteens Basin margin which existed during deposition. Hence it is not surprising that this offset is only present in the isopachs of those Members which reflect differential subsidence between the Broad Fourteens Basin and the Anglo-Dutch Basin (i.e. the Solling Mudstone Member and Riff Sandstone Member, encl. Maps 2 and 3).

The thickness distribution of the Riff Sandstone Member supports the interpretation of this offset as a syn-depositional basin margin. The main area of deposition of the Member is in the north of Quadrant 43 and in Quadrants P and Q (encl. Map 3). The thickest development of the Member, however, occurs outside these areas, in well L/10-1, immediately on the basinward side of this offset. This may represent localised clastic deposition off a syn-sedimentary basin margin (fig. 5.3).

2.4 Post-depositional Structures

Within the study area, the middle Triassic sediments are currently separated into sub-basins by the Cleaver Bank High and the Texel-Ijsselmeer High (encl. Map 1). The thickness distribution of the Dowsing Dolomitic Formation Members confirms previous authors interpretations that these structures are the result of post-Triassic uplift and erosion, rather than depositional highs (Chapter 1 section 4.1.2). The isopachs of the non-halitic Members can generally be extended across these Highs between the sub-basins (encl. Maps 4, 13, 14 and 16). Although the halitic Members are absent in wells close to the Highs (encl. maps 5 and 15), the margins of most individual cycles within the Main Röt Halite Member are coincident (encl. Map 11), indicating that the margin against these Highs is a post-depositional dissolution feature.

The previous interpretation of the Mid-North Sea High as a middle Triassic depositional high which was subject to subsequent uplift and erosion (Chapter 1 section 4.1) is also confirmed by the middle Triassic isopachs. The non-halitic Members show a general northwards thinning towards a depositional High (encl. Maps 13, 14 and 16), although the isopachs are oblique to the present erosive margin. The coincident margins of the individual cycles of the Main Röt Halite Member also indicate a post-depositional margin to the present High (encl. Map 11).

3. STRUCTURAL MODEL

The observed middle Triassic structural features can be placed within a general model which invokes dextral transtension (extension plus wrenching) along the north-west/south-east trending faults.

Dextral wrenching resulted in subsidence in the Sole Pit Trough and in the Broad Fourteens Basin both in the Permian (Glennie 1986) and in the middle/late Jurassic (Ziegler, P. 1982b, p.65). This wrenching was associated with the formation of the Central Graben, the movement of which, at its southern end in the Southern North Sea, is taken up by a series of north-west/south-east dextral wrench faults (fig. 5.4). As rapid subsidence in the Central Graben started in the Triassic (Day *et al.* 1981, Jenkins and Twombley 1980, Ziegler, P. 1982a), it is reasonable to expect that dextral wrenching also occurred at this time on the Dowsing Fault Zone and the margin of the Broad Fourteens Basin. This wrenching was accompanied by active subsidence in the Anglo-Dutch and Broad Fourteens Basins indicating that it occurred in a generally transtensional regime.

The model fits well with the predicted orientation of dextral wrench-related structures (fig. 5.4), with the syn-depositional offset in the Broad Fourteens Basin explained as a wrench-related pull-apart feature into which a thicker clastic wedge (seen in well L/10-1) prograded.

4. SUMMARY

The major structural elements in the Southern North Sea area were formed as a result of dextral transtension along north-west/south-east trending faults.

Differential subsidence along the south-west margin of the Broad Fourteens Basin resulted in the lowermost Members of the Dowsing Dolomitic Formation being restricted to the east of this margin. Following Lower Röt Mudstone Member deposition, this Basin and the Anglo-

Dutch Basin essentially acted as a single structural unit. Differential subsidence in the Broad Fourteens Basin more-or-less ceased, only to be taken up by the similar-trending Dowsing Fault Zone further to the west. The Anglo-Dutch Basin continued to subside rapidly relative to the East Midlands Shelf throughout the middle Triassic.

CHAPTER 6

CHAPTER 6

MIDDLE TRIASSIC DEPOSITIONAL HISTORY

1. INTRODUCTION

Studies of the middle Triassic depositional history are limited by the nature of the data available. For the most part, only marginal deposits around the basin edge are exposed at outcrop, while the basin centre successions are known only from petrophysical logs. Detailed studies from such logs are restricted by the interbedded, rapidly varying lithologies which make up most of the middle Triassic in the Southern North Sea area. These have a thickness generally below both the resolution of the logging tools and the sampling interval of the cuttings logs. Hence, while variations in gross lithology (e.g. dolomitic, anhydritic, halitic or mudstone dominated sequences) can be determined either directly from the logs or by petrophysical cross-plots, detailed log facies cross-plots (as used by Al-Murani (1986)) cannot be applied to these heterogeneous, argillaceous sediments.

The only available core is from the 'Staithes-20' well which occurs on the East Midlands Shelf, away from both the centre of the basin, and from the marine access farther east. Hence the depositional environments reflected in the core are not necessarily typical of the basin as a whole. In discussing the sedimentology of the core, it should be noted that access was limited, as described in Chapter 2 section 1.3.

The environment of deposition of each Member has been determined on a regional scale by identifying the log profiles, and relating lateral and vertical changes across the basin to depositional processes. These have then been tied in to both the more precise

depositional environments found in the 'Staithes-20' well core, and to the reported literature on outcrop studies across the basin.

In this chapter, the Hardegsen unconformity marking the base of the middle Triassic is discussed first, followed by the depositional environment of the various Members (either individually or in combination) and, finally, the overall controls on sedimentation, both inside and outside the Germanic Basin, are considered.

For brevity in this discussion, the lithostratigraphic names proposed for the U.K. Southern North Sea (defined in Chapter 3) are used throughout the basin, unless the local nomenclatures give added clarity.

2. HARDEGSEN UNCONFORMITY

2.1 Germany to Poland

The Hardegsen unconformity was first recognised along the southern margin of the Germanic Basin in north Germany (Boigk 1961, Trusheim 1961). Although some early workers considered this to be of only minor importance in the most marginal areas (Wolburg 1962), it has since been recognised as a major stratigraphic break occurring over the Hunte and Eichfeld basin margin swells. Up to 200 metres of section may be missing (Schröder 1982), with the underlying Hardegsen Folge eroded and the Solling Folge directly overlying the Detfurth or even the Volpriehausen Folgen (Backhaus 1971, Gall *et al.* 1977, Herrman 1962, Richter-Bernberg 1974). Most of these authors noted that the unconformity is marked by a 'Violetten Horizont' (interpreted as an intraformational weathering horizon) that can be traced southwards into southern Germany. Trusheim (fig. 4 of 1961) shows the major stratigraphic break on a gamma-

ray correlation across the Hunte swell, and Trusheim (figs. 3 and 5 of 1963) shows this same break on a gamma-ray correlation southwards into central Germany. It is the recognition of this unconformity as a major stratigraphic break which led Trusheim (1961) to suggest that the Solling Folge should be considered along with the Röt rather than with the underlying Folgen. This proposal is supported by the palynology of Geiger and Hopping (1968) and Visscher (1966), and has been followed by the stratigraphic nomenclature of both the NAM/RGD (1980) and this thesis.

Further east, in East Germany, the Hardegsen unconformity has been recognised as a major break around the basin margin (Puff and Radzinski 1980) and over local swells within the basin (Schüler 1980). In Poland the unconformity marks a major, locally erosive, break between the Lower/Middle Buntsandstein and the overlying Röt/Muschelkalk (Fuglewicz 1980).

2.2 U.K./Dutch area

In Holland, the Hardegsen unconformity has been recognised at the base of the Solling in the area of the North Netherlands swell (text fig. 2 of NAM/RGD 1980). It was, however, considered to be unrecognisable amongst the marginal sands of the basin edge (*op. cit.* p.27). Likewise in the U.K. Sector, it was considered unrecognisable within the sheet-sand complex of the Bunter Sandstone Formation (fig. 5 of Brennand 1975, Fisher 1984). This unconformity surface in fact occurs not within, but at the top of the Bunter Sandstone Formation in the U.K. Sector, and there is some evidence that this is also the case in the Dutch Sector.

2.2.1 U.K. Sector

Due to the limited data available, the present author has no direct evidence for an angular subcrop of the Bunter Sandstone Formation against the unconformity surface. There is, however, ample evidence that successively younger Members of the Dowsing Dolomitic Formation onlap against the unconformity surface, both within the Germanic Basin as well as towards its margins.

Within the basin it is the Lower Röt Mudstone Member which onlaps the Hardegsen unconformity surface. The underlying Members of the Dowsing Dolomitic Formation (the Solling Mudstone and Riff Sandstone Members) are restricted to the Broad Fourteens Basin, but the Lower Röt Mudstone Member oversteps these to lie directly on the Bunter Sandstone Formation across both the Anglo-Dutch Basin and the East Midlands Shelf (figs. 3.5 and 3.7).

The Dowsing Fault Zone lies close to the southern margin of the Germanic Basin in the U.K. Sector, and hence the East Midlands Shelf is relatively narrow (fig. 1.2). Clastic input from the London-Brabant Massif in this area is minimal, and successively younger Members of the Dowsing Dolomitic Formation can be seen to onlap this relatively narrow Shelf. In the most marginal areas, the Main Röt Mudstone Member is almost totally overstepped, and the Muschelkalk Dolomitic Member occurs at or very close to the unconformity surface (fig. 6.1). A schematic section from the Broad Fourteens Basin to the Germanic Basin margin is shown on fig. 6.2.

2.2.2 Eastern England

In this area, the East Midlands Shelf is much wider than in the U.K. Sector (fig. 1.2), and hence the onlap is less pronounced. However,

even well away from the basin margin, the thickness distribution of the Lower Röt Mudstone Member indicates the presence of the underlying unconformity. The thickest development of this Member on the East Midlands Shelf occurs in an east-west trending zone, approximately along a latitude of 54°N (encl. Map 4). As no other Member shows an increase in thickness in this zone, it is not an area of middle Triassic differential subsidence, and hence the isopachs of the Lower Röt Mudstone Member must reflect the infill of a topographic low on the unconformity surface. Several other authors have also proposed an unconformity or hiatus at the base of the Mercia Mudstone Group across the East Midlands Shelf (in Durham: Johnson 1972, Smith 1970; in Yorkshire: Warrington 1974, Woods 1973).

Further south towards the basin margin, the Main Röt Evaporite Member oversteps the Lower Röt Mudstone Member (fig. 4.11). (This overstep equates with the pinch-out of the basal red measures of the Green Beds *(s.l.)* noted by Smith and Warrington (1971).) The angular nature of the unconformity is observed in the Ollerton area (around Kirton Brickworks) from the local B.G.S. geological map (fig. 6.3). Despite this, the accomanying sheet memoir stated that no observable unconformity is present (Edwards 1967, p.132).

Close to the basin margin, around Nottingham itself, the situation is similar to that in the U.K. Southern North Sea, with the Muschelkalk Dolomitic Member equivalent occurring almost directly on top of the Hardegsen unconformity surface. This is partially obscured by the coarser marginal clastics of the Woodthorpe and Colwick Formations which, in this area, enter the basin from the south-west (between the London-Brabant Massif and the Pennine High).

Close to the basin margin around Nottingham, several authors

have noted this unconformity at the base of the Mercia Mudstone Group (Ager 1970, Audley-Charles 1970, Warrington 1970a), and that the Colwick Formation oversteps the Woodthorpe Formation to lie directly on the Bunter Sandstone Formation (Warrington 1968, p.35) or even on Palaeozoic rocks (Strahan 1881). The Colwick Formation was then the first unit of the Mercia Mudstone Group to link the Germanic Basin and the Worcester Basin, via a sill between the Pennine High and the London-Brabant Massif (Warrington 1968).

Around Nottingham the Colwick Formation has been dated as Anisian (Chapter 4 section 6.1), and therefore in this marginal area it equates with the more basinal Muschelkalk Dolomitic Member (fig. 6.4). Hence once again, as in the Southern North Sea, it is the Muschelkalk Dolomitic Member equivalent which directly overlies the Hardegsen unconformity at the basin margin, and in this case extends beyond this margin into the Worcester Basin.

2.2.3 Dutch Sector

As the Muschelkalk Dolomitic Member (or its equivalent) directly overlies the Hardegsen unconformity near the southern basin margin both around Nottingham and in the U.K. Southern North Sea, it is reasonable to expect that the same is the case along the southern margin in the Dutch Sector. The NAM/RGD (1980) report that the Röt Formation passes laterally into sandy beds towards the margin, and that these cannot be distinguished from the underlying Main Buntsandstein Formation (which in turn cannot be divided into Folgen). Hence the two Formations are combined as the Bunter Group, somewhere within which the Hardegsen unconformity occurs (*op. cit.* p.31). The Muschelkalk Formation, however, remains recognisable near the margin where it lies directly on top of the

Bunter Group (*op. cit.* p.27).

It is not clear from NAM/RGD (1980) whether the lateral passage of the Röt Formation into the Bunter Group has been observed, or is only inferred to explain the presence of the Muschelkalk Formation directly on top of a sandstone sequence. The apparent similarity with the southern margin in the U.K. Sector is striking and hence, if the latter is the case, it seems more likely that the individual Members of the Röt Formation are overstepped southwards, and that the Hardegsen unconformity occurs at the top of the Bunter Group rather than within it. This Group would hence be synonymous with the Main Buntsandstein Formation.

2.3 Danish/Polish areas

Little data are available on the Hardegsen unconformity on the northern margin of the Germanic Basin. One interesting feature, however, is that in the Danish area there is a succession which appears to be very similar to the Bunter Sandstone Formation - Lower Röt Mudstone Member - Main Röt Evaporite Member succession of the U.K. Sector, with three sandstone/shale cycles recognised within the Danish Bunter Sandstone Formation (Bertelsen 1980).

It is suggested that these cycles equate with the Volpriehausen, Detfurth and Hardegsen Folgen and that, as in most of the U.K.Sector, the Solling Folge is absent due to overstep by the Lower Röt Mudstone Member which hence directly overlies the Hardegsen unconformity surface.

Much farther away, and hence even more speculative, is the situation in the Polish area, over 1000 km to the east. Here again, the Bunter Sandstone Formation is separated from the Main Röt Evaporite

Member by a thin mudstone which equates with the Lower Röt Mudstone Member (see section 4). No cyclicity has been reported within the Bunter Sandstone Formation, but fig 3.10 (taken from Tokarski (1965)) shows a 26 metre (85') thick sandstone sequence underlain by a 13 metre (43') thick mudstone which may represent respectively the Detfurth and Hardegsen Folgen (compare fig. 3.10 with fig. 3.8). This is highly speculative, but if correct implies that, as in most of the U.K. Sector and probably in the Danish area, the Solling Folge was not deposited in this area and hence the Lower Röt Mudstone Member onlaps the unconformity surface.

2.4 Origin of the Hardegsen Unconformity

The Hardegsen unconformity is in part a manifestation of a tectonic event, with uplift and erosion of the underlying Bunter Sandstone Formation occurring both on structural highs within the basin (e.g. the North Netherlands swell) and around the basin margin (e.g. the Hunte and Eichfeld swells). A break in sedimentation is not however restricted to these structural highs. The Bunter Sandstone Formation was deposited throughout the basin, but only in the basin centre was deposition more-or-less continuous into the Dowsing Dolomitic Formation. To the west of the Broad Fourteens Basin (in the Anglo-Dutch Basin and East Midlands Shelf), if not actual erosion, there was at least a hiatus following which successive Members of the Dowsing Dolomitic Formation overstepped one another to onlap the unconformity surface. A similar onlap by the Lower Röt Mudstone Member may also have occurred in the Danish and Polish areas.

The Hardegsen unconformity hence not only reflects a structural event, but also a sudden lowering of the erosive base level throughout

the basin. This resulted in erosion of the structural highs, non-deposition (erosion?) over areas like the Anglo-Dutch Basin and the East Midlands Shelf, and restricted continuous deposition to the structural lows. Ziegler,P. (1982a) refers to this as a tectono-eustatic event.

Onlap across the East Midlands Shelf and against the basin margins indicates a gradually rising base level during the middle Triassic. This however is far from a simple transgression as will be seen from the remainder of this chapter.

3. SOLLING MUDSTONE MEMBER (Solling Folge)

The Solling Mudstone Member is mainly developed in the area between the Broad Fourteens Basin and East Germany. The Member has been examined in this area by the present author only from gamma-ray and sonic logs of the wells shown on encl. Map 2, and from the cuttings of encl. Wells L, M and N, where it is seen to be a red-brown, locally silty and sandy mudstone. Based on these limited data, little can be added to the published information on the environment of deposition. This can however be placed within a regional context.

The Member was not deposited over the Anglo-Dutch Basin and the East Midlands Shelf, and if the same was the case towards the margin in the Danish and Polish areas (section 2.3) then deposition was restricted to the central part of the Germanic Basin. An exception to this was where a coarser clastic input (the Solling Sandstein) entered the basin from the southern margin in north Germany. Northwards this passed both laterally and vertically into the Solling Mudstone Member (Herrman 1962).

The Solling Sandstein was deposited as a deltaic sand complex, with the Solling Mudstone Member representing the prodelta mudstones

(fig. 1 of Herrman 1962). Over most of the area these mudstones show no evidence of a marine origin (the first marine faunas appear in the overlying Röt (Gall *et al.* 1977)). However, towards the east of the basin, in East Germany, marine intercalations may have occurred (fig. 4 of Puff and Radzinski 1980). Clemmensen (1979) also suggested possible marine influences in the four sandstone/shale cycles (Folgen?) recognised by Würster (1960) on the north German island of Heligoland.

The Solling Folge hence represents the first, essentially non-marine phase of the transgression which followed the erosive base-level drop that produced the Hardegsen unconformity. The first deposits to transgress this surface were deltaic basin margin sands and their prodelta lacustrine equivalents. Towards the east, possible marine intercalations from Tethys occurred. In this early stage of the transgression, sediments were restricted to the structurally low basin centre, while the surrounding areas suffered either a hiatus or active erosion.

4. RIFF SANDSTONE MEMBER

This thin sandstone unit is only locally present in the Broad Fourteens Basin close to its margin with the Anglo-Dutch Basin. Known only from the gamma-ray and sonic logs, the depositional environment of this Member is speculative. It may represent either a final marginal fluvio-deltaic influx into the Solling Mudstone Member basin, or a basal marine sand associated with the transgressive Lower Röt Mudstone Member (see section 5). Hence the non-generic name of the Member.

It is most likely that the Riff Sandstone Member represents a final coarse clastic input into the lacustrine Solling Mudstone Member basin. The Member shows many similarities with the fluvio-deltaic sands

of the Hardegsen Folge in the Dutch Sector, which also thin and pass laterally into mudstones north-eastwards from the Broad Fourteens Basin margin (fig. 3.8). Also the Member appears to interdigitate with the Solling Mudstone Member rather than the Lower Röt Mudstone Member (fig. 3.7).

Based on the thickness distribution (encl. Map 3), it can even be suggested that the Member formed from the coalescing of three (or more) small deltas. The thickest development of the Member occurs in three distinct areas; the north of Quadrant 43, in Quadrant P, and along the basin margin offset in Quadrant L (see Chapter 5 section 2.3.1). In the former areas, the Member thickens slightly from the Broad Fourteens Basin margin as a single sandstone, while farther to the north-east mudstone beds interdigitate, and the Member thins as individual sandstones pass laterally into the Solling Mudstone Member (fig. 3.7). This thickness distribution may reflect deltaic deposition: The delta top sandstones thicken basinwards towards the delta front, towards the base of which they interdigitate with, and pass laterally into, the prodelta mudstones. Between these 'deltas' the Member is very poorly developed (fig. 3.5).

The possibility that the Riff Sandstone Member is a marine-deposited sandstone is not totally discarded, as Clemmensen (1985) has described a 5 metre thick shoreline sand unit from a similar horizon in Denmark.

5. LOWER RÖT MUDSTONE MEMBER

This Member forms a distinctive horizon immediately overlying the Bunter Sandstone Formation across the majority of the East Midlands

Shelf and Anglo-Dutch Basin (e.g. fig. 3.4). It is also recognisable in the Broad Fourteens Basin where it overlies the Riff Sandstone Member (fig. 3.7). Further east, where the Riff Sandstone Member is absent, the Lower Röt Mudstone Member is not easily distinguished from the underlying Solling Mudstone Member, and is generally included as part of the Solling in the local nomenclatures of Holland and Germany (Chapter 3 section 8.9). The Member, however, can be tentatively identified in these areas as a zone of particularly high gamma-ray values immediately underlying the Main Röt Halite/Evaporite Members (encl. Wells M and N). Boigk (fig. 2 of 1959) and Wolburg (fig. 1 of 1961) similarly place this approximately 10 metre thick high gamma-ray zone within the Röt succession. Towards the basin margin in the Danish and Polish areas, the Member probably directly overlies the Bunter Sandstone Formation (section 2.3). The Member is hence of a much greater lateral extent than the underlying Solling Mudstone Member, being present throughout the Germanic Basin.

The Member was deposited under marine conditions across much of the basin. In Poland, a marine fauna has been found in the Lower Röt Mudstone Member equivalent (Fuglewicz 1980, Tokarski 1965), and towards the southern basin margin in north Germany, brackish to marine faunas have been found in grey/red/violet marly transition beds (Lower Röt Mudstone Member equivalent?) at the top of the Solling Folge (Backhaus 1971, Boigk 1959, Doubinger and Bühmann 1981). In the Danish area, wave-reworked shoreline sands occur immediately underneath this Member (Clemmensen 1985).

This marine origin of the Member also explains its higher gamma-ray response compared with the Solling Mudstone Member, as marine mudstones/shales generally contain more organic matter than their non-

marine equivalents, and hence have a higher gamma-ray response (see Chapter 4 section 2.4). A similar high gamma-ray response is exhibited by the Marine Bands within non-marine Carboniferous shales (Whittaker *et al.* 1985, p.26).

There is no evidence as to whether or not the Lower Röt Mudstone Member was deposited in a truly marine environment in the Southern North Sea area. In the 'Staithes-20' well core (encl. Well B), the basal part of the Member is composed of a sandstone with discontinuous mudstone layers and clasts (Plate 3.1). This basal lag on the unconformity surface is abruptly overlain by the majority of the Member which is a generally unlaminated red-brown mudstone. Evidence indicating the subaqueous deposition of this mudstone sequence includes the presence of possible cross-laminated dolomitic siltstones and water-escape structures (Plate 3.2), and the absence of desiccation features.

The Lower Röt Mudstone Member hence reflects the first major marine influx into the Germanic Basin from Tethys during the middle Triassic. This transgressed over the lacustrine deposits of the Solling Mudstone Member, and over previous areas of non-deposition, to onlap against the basin margins. Whether these truly marine conditions extended into the Southern North Sea area is uncertain.

Given the shape of the Germanic Basin, the low relief of its margins (witnessed by the gradual onlap of the subsequent Members), and the fine-grained nature of the sediment itself, the dominant clastic input into the basin was almost certainly in the form of wind-blown dust. This was probably also the case in the overlying Members of the Dowsing Dolomitic Formation.

5.1 Gamma-ray Profiles

It was noted in Chapter 3 section 8.5, that the simple serrated high gamma-ray profiles of the majority of the Southern North Sea area are replaced locally by a serrated funnel-shaped profile (fig. 3.9). The depositional significance of this profile is somewhat problematical.

The profile reflects a gradual upwards reduction in the argillaceous content of the Member. In the absence of FDC and SNP logs for detailed lithology determination, this profile could either represent prograding marginal clastics, or an increase in the dolomitic content towards the overlying evaporites. Both interpretations seem equally valid. This profile is developed on the East Midlands Shelf in the east-west trending topographic low on the Hardegsen unconformity surface, and on the Shelf and in the Anglo-Dutch Basin near the Dowsing Fault Zone. This distribution may reflect coarser clastic input prograding into the basin along the topographic low, and spreading out and diminishing on reaching the Anglo-Dutch Basin. Alternatively, the dominant development of the profile in the Anglo-Dutch Basin and on the East Midlands Shelf away from the basin margin may reflect an increasingly dolomitic precursor to the Röt evaporite deposits. Neither explanation is totally convincing, and the origin of this gamma-ray profile remains unresolved.

6. MAIN RÖT HALITE MEMBER

This Member has variously been interpreted as forming under continental playa-lake conditions (Gdula 1983, Lippmann 1956); from marine waters in direct connection with Tethys (Busson 1982, Hinze 1967, Richter-Bernberg 1972a, b); as a marine halite sourced from Tethys, but

precipitated in one or more isolated lagoons following withdrawal of the sea (Bertelsen 1980, Harsveldt 1978, Jacobsen 1982); as a marine halite formed in part by the re-precipitation of diapiric Zechstein salts (Trusheim 1971); and as a totally re-precipitated Zechstein halite (Ziegler,W. 1975).

Evidence for the marine origin of the Main Röt Halite Member comes from the bromine profiles of halite cores both in western Poland and the eastern Netherlands (Holser and Wilgus 1981). Bromine values range between 40 to 180 ppm, within the theoretical range for marine halites, with an overall higher mean value in the Dutch area (110 ± 45 ppm) compared with the Polish area (56 ± 9 ppm). The profiles lack the smooth trends of a deep-water brine, suggesting deposition in a shallow basin in both areas; however, they do not show the wildly erratic profiles indicative of periods of complete desiccation (*op. cit.*).

Very low bromine values (1-20 ppm), indicative of a re-worked Zechstein source for the salt, are not found (*op. cit.*). Similarly, the isopach maps of the Röt Members do not show rapid thickness variations which would indicate diapiric Zechstein salt movements (encl. Maps 4 to 13). Even if salt movements had begun by this time (as suggested by Brunstrom and Walmsley (1969), Glennie (1986) and Ziegler,W. (1975)), there is a considerable difference between the formation of local salt swells, and the formation of diapirs piercing through over 600 metres of Bacton Group sediments to source the Main Röt Halite Member.

The higher average bromine values in the eastern Netherlands, compared with western Poland, indicate higher salinities in the former area. This is in keeping with the distribution of the evaporite facies. In eastern Poland reef limestones are found at the entrance to Tethys (Richter-Bernberg 1972a). These pass westwards into anhydrites and

dolomites (Tokarski 1965), while further west, in East Germany, the succession is one of dominantly anhydrites and halites (Docter *et al.* 1980). In the study area, halites dominate the sequence almost to the total exclusion of the earlier evaporite facies (e.g. encl. Wells A and M). This lateral gradation in evaporite facies reflects the increased salinity across the basin (fig. 6.5).

Several authors have noted that a lateral salinity gradient could exist across a single evaporite basin (without internal barriers) provided there were shallow water depths and a vast lateral distance between the marine source and the inner parts of the basin (Friedman 1980, Holser 1979). Under such conditions, water entering the basin would precipitate the earlier evaporite facies near the entrance, before moving on to precipitate the later evaporite facies further into the basin. This 'saturation shelf' model has been applied to the +1000 km wide Germanic Basin by Busson (1982) and Richter-Bernberg (1972a, b).

From a detailed study of the petrophysical logs, it is possible to considerably refine and expand upon this basic model for the deposition of the Main Röt Halite Member. It can be shown that the halite was deposited in a series of cycles, some of which formed within a single extensive evaporating basin, probably in direct connection with Tethys, while others formed in lagoons periodically isolated from the marine source. Individual cycles resulted from a rapid marine transgression followed by a gradual regression, while the Member as a whole reflects a gradual expansion and then contraction of the halite basin.

The present distribution of the Main Röt Halite Member is shown on encl. Map 5.

6.1 Halite Cycles

The Main Röt Halite Member can be subdivided by means of thin zones of high gamma-ray and sonic values which are indicative of mudstones. These 1 to 2 metre-thick mudstones, separated by up to 20 metres of halite, are regionally correlative, not only within the U.K. Sector (fig. 3.6), but throughout the study area (fig. 6.6), and allow subdivision of the Member into up to six units.

Between these mudstones, the succession is dominated by relatively pure halites, identified by their distinctive blocky sonic log response (with Δt values close to the halite Δt_{ma} of 67 μ.sec/ft). However, immediately overlying each mudstone, the sonic log frequently shows Δt values slightly lower than those of the overlying halites (the U.K. Sector well on fig. 6.6 shows this particularly clearly). This is interpreted as a dolomitic/anhydritic horizon (no other lithologies in an evaporite sequence have lower Δt values than halite). True dolomitic/anhydritic Δt responses are not developed, due either to the thinness of these beds (below the resolution of the logging tool), or the presence of halite interbedded with the dolomites/anhydrites.

Each unit hence contains a mudstone, overlain first by a thin dolomitic/anhydritic horizon and then a thick halite. This is comparable with the predicted vertical succession which would be precipitated in a subaqueous evaporite basin setting (Holser 1979), although in this inner part of the Germanic Basin the carbonates and sulphates are poorly represented.

Each unit is hence an evaporite cycle. The basal mudstone represents the continuous, fine-grained, subaqueously deposited (wind-blown?) background sedimentation which, with increasing salinity, was

blanketed out by the more rapid precipitation of dolomites/anhydrites and finally halites. K/Mg salts (low sonic, but very high gamma-ray values) have not been observed, indicating either that these salts were dissolved at the start of the succeeding cycle or that the evaporite cycles did not go to total desiccation. K/Mg salts may have developed locally in the Danish area (Jacobsen 1982).

Towards the halite basin margins, individual cycles may become increasingly impure, with a greater percentage of mudstone and interbedded dolomite/anhydrite (fig. 3.11). At the margin, the Main Röt Halite Member passes laterally into the dolomitic/anhydritic Main Röt Evaporite Member, although in general, individual dolomites/anhydrites cannot be correlated with specific evaporite cycles (fig. 6.6).

Up to five major halite cycles occur within the Main Röt Halite Member (Cycles A to E), the last of which can be seen to pass laterally into the Main Röt Evaporite Member (fig. 3.6). The dolomites overlying this cycle (up to the top of the Main Röt Evaporite Member) are tentatively termed 'Cycle F', although this is only halitic in one well in the Sole Pit Trough.

Previous authors have recognised that the Main Röt Halite Member could locally be subdivided and correlated by means of the mudstone interbeds, both in eastern Holland (Cox 1963, Harsveldt 1978) and in north Germany (Trusheim 1971), although no explanation for the subdivision was presented.

6.2 Single v. Multiple Halite Basins

The present distribution of the Main Röt Halite Member is in several separate halite basins (encl. Map 5) which are surrounded by

wells containing the dolomitic/anhydritic sequence of the Main Röt Evaporite Member. This latter Member does not always represent a depositional fringe to the halite basin, as in some wells (e.g. the 'Staithes-20' well (encl. Well B)), the Member comprises a collapse breccia, the result of halite dissolution. Depositional margins can be distinguished from these dissolution margins resulting from near-by post-Triassic uplift, by comparing the thickness and lateral distribution of individual halite cycles. Depositional margins are interpreted in those areas where cycles thin gradually towards the margin, and where some individual cycles extend beyond others (fig. 6.7). Post-Triassic dissolution margins are inferred in those areas where individual cycles end abruptly without gradual thinning, and where several cycles end at the same point (fig. 6.8).

Some cycles extend beyond others towards the south-west margin in the U.K. Sector between Quadrants 47 and 49, and in the centre of the Southern Dutch Sector (encl. Map 11). These are interpreted as depositional margins. Post-Triassic dissolution margins are present in many (but not all) cycles against the Cleaver Bank High (both in the U.K. and Dutch Sectors), and against the Texel-Ijsselmeer High, indicating that these are post-depositional structures (the apparent depositional margins are explained in section 6.4). Presumably the dolomitic/anhydritic Main Röt Evaporite Member in the wells close to these structures comprises collapse breccias. The margin against the Mid-North Sea High appears to be a combination of both a depositional and dissolution margin, with some cycles extending beyond others towards the margin, but an abrupt end to all the remaining cycles near the High (encl. Map 11).

Halite depositional margins hence occur towards the edge of the

Germanic Basin, but not normally against structural highs within the basin, implying that the Main Röt Halite Member was, to a large extent, deposited in a single evaporite basin which extended throughout the study area (and possibly the whole Germanic Basin). Further evidence that a single Main Röt Halite Member basin existed from the U.K. to north Germany, is the recognition of the same halite cycles throughout the study area (fig. 6.6).

6.3 Nature of Individual Cycles

The maximum thickness of individual cycles in the U.K. and Southern Dutch Sectors is about 20 metres, of which the vast majority is halite. As it would take a column of over 1500 metres of sea-water to precipitate such a thickness of halite from an isolated body of marine water (Schreiber 1986, p.191), there was obviously a connection with Tethys, and continued influx of new marine water into the Germanic Basin during the deposition of each cycle. During each cycle evaporation was greater than influx and hence precipitation moved forward through the evaporite facies from dolomites/anhydrites to halites.

The influx/evaporation balance can be examined in more detail by using the FDC log as an apparent salinity indicator (the basis for this is described in Appendix C). From this log, it is evident that the majority of the Main Röt Halite Member cycles have an asymmetrical development, with a gradual increase of salinity through the cycle, followed by a rapid decrease in salinity at the start of the following cycle.

This asymmetry is seen from the FDC log of well 48/12-1 (encl. Well A). In this well, Cycle D (and to a lesser extent Cycle B) shows a

gradual decrease in density (which reflects a gradual increase in salinity) upwards into the cycle, followed by an abrupt increase in density (decrease in salinity) into the mudstone marking the start of the following cycle. The FDC log is rarely available in the Main Röt Halite Member, but a similar feature is often seen from the sonic log, with a gradual change from mudstone to dolomite/anhydrite to halite into the cycle, but a rapid change from halite directly back to mudstone at the top of the cycle. Cycle A appears to have a more symmetrical development, with the dolomitic/anhydritic facies developed both at the base and top of the cycle (as seen from the sonic log of wells 43/21-1 and 43/17-1 on fig. 3.6).

Assuming that evaporation remained more-or-less constant, the evaporite sequence reflects a gradual decrease in the amount of influx entering the basin through each cycle. At the top of Cycle A there was a gradual increase in the rate of influx; precipitation once again passed through the dolomite/anhydrite facies, until finally precipitation ceased and the background mudstone sediments accumulated marking the start of Cycle B. The higher cycles within the Member again show this successive development of higher evaporite facies, but in these cycles there is an abrupt end to the evaporite precipitation, resulting from a rapid increase in the amount of influx entering the basin at the start of the next cycle. The cycles hence reflect rapid basinwide transgressions followed by gradual regressions.

6.4 Development of the Halite Basin

The Main Röt Halite Member basin expanded in size from Cycle A, through Cycles B and C, and then shrank again through Cycles D and E

(encl. Map 11).

6.4.1 Cycle A

Cycle A is essentially restricted to the more rapidly subsiding structural lows such as the Sole Pit Trough and the Broad Fourteens Basin (encl. Map 6). It is also tentatively identified in the rapidly subsiding Central Graben (Northern Dutch Sector), and in the Ems Trough of north Germany. The margin against the Cleaver Bank High in the U.K. Sector does not coincide with that of the overlying cycles, and is hence considered depositional (encl. Map 11). This first halite cycle was therefore deposited in a series of structurally controlled isolated depressions across the study area.

Several authors have suggested that thickness variations in the Main Röt Halite Member as a whole reflect the infilling of depressions left on the Hardegsen unconformity surface (Fisher 1984, Harsveldt 1978, Ziegler,W. 1975). The distribution of Cycle A indicates that this is not the case (such depressions would anyway be infilled by the Solling Mudstone and Lower Röt Mudstone Members rather than the Main Röt Halite Member). Deposition occurred in active structural lows (e.g. the Sole Pit Trough) which subsided throughout much of the middle Triassic, rather than in passive topographic depressions on the Hardegsen unconformity surface.

6.4.2 Cycle B

Cycle B was the first of the halite cycles to be deposited throughout the study area. The margin of this cycle against the Cleaver Bank High in the U.K. Sector is essentially coincident with that of the overlying cycles (encl. Map 11), although in Quadrant 49 the halite thins

towards this margin (encl. Map 7). This implies that the margin is in part depositional, rather than solely the result of post-Triassic dissolution. Further north, no such thinning towards the Cleaver Bank High is observed. Cycle B may hence have been deposited, in the U.K. Sector, in a lagoon which was separated from the more extensive halite basin to the east by the proto-Cleaver Bank High. However, no other cycles of the Main Röt Halite Member show evidence of thinning towards an active Cleaver Bank High (encl. Maps 8, 9 and 10), and hence an alternative interpretation is preferred.

The preferred interpretation is that this depositional margin of Cycle B, in the U.K. Sector, occurred not against a proto-Cleaver Bank High, but against the structurally high eastern edge of the Anglo-Dutch Basin. This basin can be considered as an enormous tilted half-graben with maximum subsidence towards the west against the Dowsing Fault Zone, and minimum subsidence towards the east close to its margin with the Broad Fourteens Basin. The depositional margin of Cycle B was hence against this structurally high edge of the tilted fault-block (fig. 6.9). Towards the north-east in Quadrant 44, this 'high' disappeared and halite deposition was continuous from the Anglo-Dutch Basin to the Broad Fourteens Basin (encl. Map 7).

From this model it is evident that the apparent depositional margin against the Cleaver Bank High should only occur where this High overlies the eastern edge of the Anglo-Dutch Basin. This is indeed the case. Further north where the eastern edge of the Anglo-Dutch Basin no longer coincides with the Cleaver Bank High, an apparent depositional margin against the High is not observed (encl. Map 7). The halite basin of the U.K. Sector was probably connected through this latter area with the basin in the east, and hence deposition of Cycle B probably occurred

in a single basin extending throughout the study area.

6.4.3 Cycle C

Cycle C covers a slightly larger area than Cycle B (encl. Map 8). The margin against the Cleaver Bank High in the U.K. Sector is abrupt, with little evidence of thinning, and is hence the result of post-Triassic dissolution. There is no evidence for a depositional margin against the eastern edge of the Anglo-Dutch Basin in Quadrant 49 (similar to that seen in Cycle B). This is in keeping with the fact that this Basin and the Broad Fourteens Basin increasingly acted as a single structural unit through the middle Triassic (Chapter 5 section 2.3). Cycle C was hence deposited in a single basin which extended throughout the study area.

6.4.4 Cycle D

The areal extent of the halite basin was reduced during Cycle D deposition (encl .Map 9). The margin against the Cleaver Bank High once again appears to be the the result of post-Triassic dissolution, and hence this cycle was also deposited in a single basin which extended across the study area.

6.4.5 Cycle E

The halite basin was further reduced in size during the deposition of Cycle E (encl. Map 10). This cycle is restricted to the central part of the basin in the U.K. and Northern Dutch Sectors and is absent further to the east. As there is no evidence for a depositional margin against the Cleaver Bank High, this cycle was probably deposited in a single isolated lagoon restricted to the Southern North Sea area.

6.4.6 Summary

The overall development of the Main Röt Halite Member basin was hence one of expansion from isolated structurally controlled lagoons in Cycle A, through a single basin of increasing and then decreasing size in Cycles B to D, and back to an isolated lagoon in Cycle E. This development is also reflected by the thickness of the individual cycles. Lagoonal cycles A and E (encl. Maps 6 and 10) are generally thinner than the basinwide cycles B, C and D (encl. Maps 7, 8 and 9). During the latter cycles the Germanic Basin was probably in direct connection with Tethys throughout the cycle, hence the influx of new marine water was more-or-less continuous, resulting in the precipitation of a thick halite. During the isolated lagoonal cycles, influx across the vast playas surrounding the lagoons would have been episodic and hence a generally thinner halite sequence was formed in all but the most rapidly subsiding areas.

The precipitation of Cycles A and E in isolated lagoons with periodic rather than constant replenishment does not affect the concept of the lateral salinity gradient across the Germanic Basin, provided that the source of the marine water remained from the east. During times of replenishment the gradient would exist, and hence new marine water filling the isolated lagoons in the Southern North Sea area would already be depleted in carbonates and sulphates. A similar model with carbonates and sulphates deposited in separate basins nearer to the marine source, has been proposed to explain the lack of these evaporites in the upper Triassic halite deposits on the western periphery of Tethys (Grand Banks area) (Jansa *et al.* 1980).

6.5 Depositional Model

The Main Röt Halite Member was deposited in a vast shallow basin, from marine waters which entered from Tethys via eastern Poland. A lateral salinity gradient, which existed across the basin, resulted in dominantly carbonates and sulphates being precipitated in the east of the basin, and dominantly halites towards the west.

The Main Röt Halite Member was formed from several halite cycles which reflect an expansion and contraction in the area of halite deposition. The lowermost cycle was deposited in a series of isolated lagoons restricted to tectonic depressions. The following three cycles, deposited throughout the study area in a single evaporite basin, reflect an expansion, followed by a contraction, in the area of halite deposition. Further contraction resulted in the final main cycle being deposited in a single lagoonal setting restricted to the centre of the Germanic Basin in the U.K. and Dutch areas.

The overall expansion and contraction of the halite basin through successive cycles, along with the presence of basin-wide cycles sandwiched between lagoonal cycles indicates an increase then decrease in the water depths within the basin. Such a large-scale fluctuation is most likely the result of a gradual eustatic sea-level rise and then fall within Tethys.

The individual halite cycles are the result of smaller-scale fluctuations on the back of this major eustatic trend and probably have a similar eustatic origin. They are, for the most part, asymmetrical, reflecting a rapid sea-level rise followed by a gradual sea-level drop. An alternative origin for this cyclicity could possibly be tectonic activity near the entrance to Tethys, or periodic growth of the carbonate

reefs reported in this area (Richter-Bernberg 1972a). A eustatic origin is considered more likely in light of the frequent cyclicity exhibited by other Members of the Dowsing Dolomitic Formation (see section 15).

A modern, although considerably smaller scale, analogue for the cyclicity in the Main Röt Halite Member is found in the 160 km wide Karabogaz-Gol in the southern USSR (Dzens-Litovskiy and Vasil'yev 1962). This almost totally enclosed basin has no fluvial input, and is connected to the Caspian Sea by a narrow strait. Subaqueous evaporite precipitation in the basin has occurred in four cycles over the last 10,000 years, the thickest of which reaches 16 metres. These cycles have been related to Caspian Sea level changes. Detailed annual measurements on the modern basin have identified a pronounced lateral salinity gradient, with the highest salinities farthest from the entrance. At the start of the last cycle (in 1939) carbonates and gypsum were precipitated near the entrance to the basin, while halite precipitated further in (*op. cit.*).

7. MAIN RöT EVAPORITE MEMBER

The Main Röt Evaporite Member comprises dolomites, anhydrites and dolomitic/anhydritic mudstones which in some areas are the lateral equivalent of the Main Röt Halite Member (fig. 6.6), and in other areas are collapse breccias associated with post-depositional dissolution of the halite Member (fig. 6.8). The resulting highly serrated log profiles are indistinguishable. Those areas of probable collapse breccias are discussed in Chapter 5 section 2.1, and in this chapter in section 6.2. The only cored well, 'Staithes-20' (encl. Well B), is in one such area. These collapse breccias are excluded from the discussion below.

As the lateral equivalent of the Main Röt Halite Member, the

Main Röt Evaporite is known only from its log responses in the sub-surface, and from the literature at outcrop. The former allow basic identification of lithologies, but offer little direct information on the depositional environment.

The Member forms a fringe to the halite basin which is recognised throughout the U.K. Southern North Sea area until its eventual onlap against the Germanic Basin margin (as shown on encl. Map 5 and fig. 6.1). Immediately around the halite basin, the dolomitic/anhydritic beds may have formed by subaqueous precipitation, with the interbedded mudstones representing the influxes of new marine water at the start of each cycle. The lateral salinity gradient would restrict the size of this subaqueous fringe, and hence it is likely that most of the Member was deposited as a coastal sabkha sequence surrounding the evaporite basin. The log profiles of this would be indistinguishable from those of the subaqueous basin margin evaporites.

Friedman (1980) noted that in broad, shallow epeiric basins with low tidal and wave activity, the lack of shoreline deposits blurs the distinction between marine and non-marine evaporites, with sabkhas prograding over marine evaporites during periods of regression. Such a complex interdigitation of marine and non-marine evaporites may be reflected by the Main Röt Evaporite Member of the Germanic Basin.

At outcrop in England, the Member equates with the Retford Formation (formerly Green Beds) of Warrington *et al.* (1980). This Formation comprises ripple-marked mudstones and sandstones which pass basinwards into mudstones with gypsiferous/anhydritic horizons up to three metres thick (Smith *et al.* 1973, p.178, Warrington 1974, p.155). These evaporites have been identified as far south as 12 km south of the 'Torksey-4' well (Smith and Warrington 1971), which coincides with the

area where the Formation becomes diachronous (see Chapter 4 section 6.1). Hence, the more marginal current-deposited succession probably formed synchronously with the Intermediate Röt Mudstone Member, while the more basinal gypsiferous/anhydritic mudstones formed as a siliciclastic sabkha fringe to the Main Röt Halite Member basin (fig. 6.4).

In the Danish area, the Main Röt Halite Member similarly passes laterally into evaporitic mudstones (Bertelsen 1980) which have been interpreted as large coastal sabkhas (Jacobsen 1982).

8. INTERMEDIATE RÖT MUDSTONE MEMBER

The Intermediate, Upper and Main Röt Mudstone Members are discussed together in section 10.

9. UPPER RÖT HALITE/EVAPORITE MEMBERS

The Upper Röt Halite Member is considerably thinner than the Main Röt Halite Member, but shows many similarities in both lateral and vertical development. Laterally, the Member passes into the dolomites/ anhydrites and mudstones of the Upper Röt Evaporite Member and, vertically, a thin mudstone near the base of the Member may reflect the boundary between two evaporite cycles. The lower cycle is only tentatively identified as about 2 metres thick in most, but not all wells in the U.K. Sector (fig. 3.6). The upper cycle forms most (and in some wells possibly all) of the Member.

The vertical sequence of mudstone - dolomite/anhydrite - halite seen in the Main Röt Halite Member cycles is rarely well developed in the Upper Röt Halite Member, although it may be present in well 42/28-2

(encl. Well G). More obvious is the lateral development of this sequence, with the halites of the basin centre passing outwards into a 40 to 60 km wide zone of dolomites, anhydrites and dolomitic/anhydritic mudstones (the Upper Röt Evaporite Member), which in turn pass outwards into the mudstones of the Main Röt Mudstone Member (encl. Map 12, fig. 3.14). This lateral succession is similar to the classic bulls-eye pattern of a sub-aqueously deposited evaporite sequence, but more likely results from a subaqueous halite basin surrounded by a fringing supratidal sabkha which in turn passes towards the hinterland into playa mudstones.

Within the U.K. Sector, the Upper Röt Halite Member (encl. Map 12) has a similar areal extent to Cycle E of the Main Röt Halite Member (encl. Map 10). However, basinwide the Upper Röt Halite Member is much more extensive, occurring not only in the Southern North Sea area, but locally in one well in the Northern Dutch Sector, and also across north Germany, where it has a similar thickness. It may extend locally into East Germany (encl. Map 12), where it passes into a gypsum and anhydrite dominated sequence (Docter *et al.* 1980), which is also present in Poland (Fuglewicz 1980, Tokarski 1965). This lateral gradation from sulphates in the east of the basin to chlorides in the west, once again implies the development of a lateral salinity gradient across the basin, from the marine source in eastern Poland.

It is difficult to be certain whether the Upper Röt Halite Member was deposited in a single evaporite basin extending across the study area, or in separated lagoons. The former is more likely, as U.K. Sector well 44/24-1 lying close to the Cleaver Bank High, and eastern Netherlands well 'Blijham' lying close to the Texel-Ijsselmeer High, both show thicknesses comparable with the centre of their respective basins, suggesting that the margins against these structures are dissolutional

not depostional (encl. Map 12). It is hence probable that the Upper Röt Halite Member was deposited in a single evaporite basin which was linked to, and sourced by, marine waters which entered the Germanic Basin from Tethys via eastern Poland. As a result, presumably of the lateral salinity gradient, carbonates and sulphates are poorly represented in the Southern North Sea area.

Only the Upper Röt Evaporite Member is present in the cored 'Staithes-20' well (encl. Well B). The Member is dominated by red-brown anhydritic mudstones, with occasional thin interlaminated dolomites/ dolomitic mudstones. This latter facies is probably of subaqueous origin (see discussion in section 10.2.1), while the anhydritic mudstones may be of a supratidal origin. A proposed sabkha cycle is shown on Plate 3.9. The cycle starts with a subaqueous laminated dolomite, followed by a highly disrupted anhydritic mudstone, overlain by a less anhydritic, generally unlaminated mudstone. Two cycles are tentatively recognised in the core, and may coincide with the two cycles present in the halite basin.

Across the basin, a thin development of the Upper Röt Evaporite Member overlies the Upper Röt Halite Member (fig. 3.14). Hence following the subaqueous precipitation of the halites, the marginal sabkhas of the Upper Röt Evaporite Member prograded across the centre of the basin.

10. INTERMEDIATE/UPPER/MAIN RÖT MUDSTONE MEMBERS

This discussion refers to the whole sequence from the top of the Main Röt Evaporite Member to the base of the Muschelkalk Dolomitic Member (excluding the Upper Röt Halite/Evaporite Members). Towards the basin centre where these latter Members are present, the sequence is

divided into the Intermediate and Upper Röt Mudstone Members, and towards the margin where they are absent, the whole sequence forms the Main Röt Mudstone Member (fig. 3.1).

From the petrophysical and cuttings logs, the Member is identified as a succession of dolomitic, silty, locally anhydritic mudstones in the U.K. Sector, and similar log profiles indicate comparable lithologies throughout the study area (e.g. compare encl. Wells A, L and N). Unfortunately these logs offer little, if any, information on the depositional environment. The Member has, however, been studied by several authors at outcrop between Poland and the U.K., although in the latter area detailed subdivision of the Mercia Mudstone Group away from the basin margin has not previously been considered possible (Chapter 4). It is hence difficult to equate the outcrop studies of previous authors specifically to this Member. In the cored 'Staithes-20' well, however, the Member is clearly identified on the petrophysical logs (encl. Well B), and this allows a direct comparison between the sedimentology of this Member on the East Midlands Shelf, and its reported development in the centre and east of the basin.

10.1 Basinwide Development

Towards its access with Tethys in eastern Poland, the Member is developed in a carbonate facies, comprising limestones, dolomites and marls. These contain a marine fauna (Fuglewicz 1980, Senkowiczowa 1961, Ziegler,P. 1982a), with normal open-marine conditions gradually increasing upwards towards the Muschelkalk (Tokarski 1965). This Röt profile is shown on fig. 3.10. Farther west, in East Germany, the Member comprises silty dolomitic mudstones (similar to those deposited over most

of the Germanic Basin). These too were deposited under marine conditions (Althen *et al.* 1980, Schüler 1980).

Further across the basin, in north Germany, marine influences are again recognised throughout the Member, although rather than being continuous, they reflect cyclic advances and retreats of the sea in a generally hypersaline environment (Backhaus 1971, Doubinger and Bühmann 1981, Paul and Franke 1977). During periods of marine transgression, dolomitic oolite banks (up to 0.5 metres thick) formed locally (Hinze 1967, Ritzkowski 1978). Towards the southern basin margin, the first marine influences occur increasingly higher up within the Member, reflecting the gradual southwards passage of marine conditions (Backhaus 1971, 1981, Lippmann 1956).

In the Southern North Sea area, the Member has been variously interpreted as having formed under subaqueous and supratidal conditions, in environments varying from marginal marine to continental playa (Bertelsen 1980, Gdula 1983, Ziegler,P. 1978).

In the most marginal areas of eastern England around Nottingham, the lowermost Mercia Mudstone Group is diachronous (Chapter 4 section 6.1), with both the Woodthorpe and overlying Colwick Formations being deposited synchronously with the Anisian Muschelkalk Dolomitic Member. Deposition synchronous with the Main Röt Mudstone Member hence did not occur in this area (fig. 6.4). Further north, where detailed subdivision of the Mercia Mudstone Group has not previously been possible, marine microplankton are reported from the lower part of the Group, which includes the Main Röt Mudstone Member equivalent (Smith *et al.* 1973, p.186; Smith and Warrington 1971; Warrington 1968; 1974, p.154; 1981).

10.2 'Staithes-20' Well Core

Examination of the 'Staithes-20' well core (encl. Well B) offers considerably more insight into the depositional environment of the Member on the East Midlands Shelf. Two distinct facies, a laminated dolomite/mudstone and a blocky mudstone facies make up both the Intermediate and Upper Röt Mudstone Members. These facies are closely comparable with similar facies reported from semi-arid to arid playa mudstone sequences both ancient and modern (Arthurton 1980, Demicco and Kordesch 1986, Hubert and Hyde 1982, Kendall 1979a, Schreiber 1986, Tunbridge 1984). Based on these similarities, the laminated and blocky facies are respectively interpreted as subaqueous lagoonal and subaerial playa mudflat deposits.

10.2.1 Laminated Facies

10.2.1.1 Description

The laminated facies comprises thinly interbedded green-grey argillaceous dolomites and green-grey to red-brown dolomitic mudstones (Plate 3.5). The dolomites vary from relatively silt-free to silty dolomites and dolomitic siltstones and are frequently anhydritic. Individual dolomite beds are generally up to 2 cm thick, although they may reach up to 6 cm. The facies as a whole rarely exceeds 50 cm thickness.

The tops and bases of the dolomitic layers are generally abrupt. Flat and irregular contacts occur. The latter reflect soft-sediment loading on the base of the dolomites, and the wavy tops may indicate an upper rippled surface (Plate 3.5). Internally, the dolomites are generally flat to slightly wavy-bedded. Occasionally, they show

small-scale cross-lamination, and may grade into the overlying mudstone.

The interbedded dolomitic mudstones vary from silty to relatively silt-free, and may be anhydritic with nodules, up to 3 cm long, elongated parallel to bedding. The mudstones may show horizontal lamination, but are often unlaminated.

The laminated facies as a whole is affected by various syn-sedimentary deformation features. The most common are subvertical fractures which penetrate down into the laminated facies, usually from its upper surface, but which occasionally penetrate down from one of the thin mudstones within the facies (Plates 3.5 and 3.11). These fractures may be up to 1 cm wide, taper downwards, and are filled with red-brown mudstone. They show many of the features indicative of desiccation cracks. They are subvertical, have generally straight sides, and frequently show up-turned edges at their upper end (Plate 3.11). Occasionally (at 1885' in the core) the cracks show evidence of multiple opening and filling.

Water-escape structures are another frequently observed soft-sediment deformation feature. Generally these result in the buckling and subsequent local erosion of the tops of individual dolomites prior to the deposition of the next bed. An extreme example is shown on Plate 3.8. Here escaping water has severely buckled and broken through the overlying dolomite. The whole surface has then been eroded flat prior to the deposition of the following laminated dolomites and mudstones.

The final soft-sediment deformation feature observed is related to water escape. This is soft sediment slumping. One example has been observed in the Intermediate Röt Mudstone Member (Plate 3.6), where an overpressured mudstone has buckled the overlying dolomite. The asymmetrical nature of the buckling implies that this is a slump rather

than a simple water-escape structure.

10.2.1.2 Interpretation

The various sedimentary structures indicate that this facies was subaqueously deposited. The small-scale cross-lamination reflects the presence of currents within the basin. There is no evidence that the source of the currents or the sediments are from fluvial input, as none of the sediments are coarser than fine silts (which could well have a wind-blown origin). The slumping, water-escape structures and the loading on the base of the dolomites indicate their fairly rapid deposition.

The desiccation cracks are out of keeping with this subaqueous origin of the laminated facies. The majority, however, penetrate down from the top of the facies, and hence are related to the overlying blocky facies. Those desiccation cracks that extend down from a mudstone within the laminated facies indicate brief periods of subaerial exposure.

The nodular anhydrites within the mudstones may either have formed internally within the laminated facies during deposition of the blocky facies, or may have formed interstitially beneath the lagoon during the deposition of this laminated facies. This is discussed further in section 11.1.1.

10.2.2 Blocky Facies

10.2.2.1 Description

This facies is composed of red-brown silty dolomitic mudstones. Anhydrite nodules are common. Lamination is rare, especially in the upper part of the facies. Towards the base, zones of disrupted lamination may be present. Zones of apparently brecciated mudstone also occur, usually towards the base of the facies. This facies is generally thicker than the

laminated facies, varying from about 10 cm to over 3.5 metres.

Desiccation cracks are often difficult to identify, due to the lack of contrast between the mudstone matrix and the mudstone infill. They are, however, seen on bedding planes (Plate 3.10), and where there is a contrast between the infill and matrix.

10.2.2.2 Interpretation

The evidence of desiccation, the nodular anhydrite, and total lack of subaqueous sedimentary features, suggest deposition in a subaerial environment. The sediments closely conform to the playa mudstone sequences described by Arthurton (1980) for the Mercia Mudstone Group of the Cheshire basin, and this model is adopted here. The blocky facies hence accumulated in supratidal conditions from wind-blown sediments which adhered to the damp playa surface. Anhydrite grew displacively within these sediments. Demicco and Kordesch (1986) noted that playa mudstones frequently have highly disrupted fabrics resulting from repeated wetting and desiccation of the surface of the playa. The disrupted (brecciated) mudstones of the Intermediate and Upper Röt Mudstone Members may have a similar origin.

10.2.3 Cyclicity

The laminated and blocky facies reflect a cyclic alternation between lagoonal and playa mudflat deposition. Approximately 20 cycles can be identified.

There is generally an abrupt contact at the base of the laminated facies, whereas the top is often less distinct, with desiccation cracks penetrating down from the overlying blocky facies, which in turn may show disrupted and brecciated lamination towards its

base. Arthurton (1980) identified a similar association from the Mercia Mudstone Group of the Cheshire Basin. This he related to a cyclicity which started with the deposition of the subaqueous laminated facies, followed by a gradual progradation of the subaerial playa-flat mudstones of the blocky facies. Two features (also valid for the Main Röt Mudstone Member) indicated this shallowing sequence (*op. cit.*). Firstly, the disrupted laminations at the base of the blocky facies resulted from slight re-working of the laminated facies; and secondly, the disrupted/ brecciated mudstones, the result of repeated desiccation, were often restricted to the lower part of the blocky facies, implying that the overlying more massive mudstones were deposited farther from the water-body.

The laminated facies presumably contains the marine micro-plankton reported from eastern England by Smith *et al.* (1973), Smith and Warrington (1971), and Warrington (1968, 1974, 1981), and hence indicates that the intermittent marine influences noted in the north German area (Backhaus 1971, Doubinger and Bühmann 1981) extended even to this most distal part of the basin. Whether the subaqueous deposition occurred in laterally continuous standing bodies of water, or in isolated lagoons periodically replenished by marine flooding is uncertain. The latter is however more likely, as correlation of log profiles between wells within this Member is impossible, whereas there is a high degree of correlation in the (restricted) marine deposits of the Muschelkalk Dolomitic Member.

10.2.4 Mega-cycles

Compound cycle associations are present in the core on both small and large scales. On the small scale, individual 20 to 50 cm cycles may be grouped together showing a gradual increase or decrease in the

percentage of the laminated facies upwards over a few metres.

On the largest scale, the whole Intermediate Röt Mudstone Member reflects a major regressive cycle, and the whole Upper Röt Mudstone Member reflects a major transgressive cycle. It is evident from the core log (encl. Well B), that the percentage of the subaqueous laminated facies decreases upwards throughout the Intermediate Röt Mudstone Member until, in the upper part, the subaerial blocky facies dominates the Member. The reverse is the case in the Upper Röt Mudstone Member, the blocky facies dominates in the lower part of the Member and the laminated facies in the upper part.

10.3 Summary

The intermittent marine influences in the Main Röt Mudstone Member reported from north Germany, extended to the East Midlands Shelf, where alternations between subaqueous and subaerial deposition occurred. Sea-level fluctuations were cyclic, with mega-cycles occurring on a scale from a few metres to tens of metres. The Intermediate Röt Mudstone Member represents a major regressive cycle, and the Upper Röt Mudstone Member a major transgressive cycle. The latter cycle heralds the marine conditions of the Muschelkalk Dolomitic Member, and coincides with the gradual extension of marine conditions over much of the Germanic Basin (Backhaus 1971, 1981, Lippmann 1956, Tokarski 1965).

11. MUSCHELKALK DOLOMITIC MEMBER

Deposition of the Muschelkalk Dolomitic Member and its litho-stratigraphic equivalent the Lower Muschelkalk, indicates the

establishment of more continuous marine conditions across the Germanic Basin. Marine access from Tethys was once again via eastern Poland (Ziegler,P. 1975a, b, 1982a), and between this area and north Germany, two major facies were developed. The first facies comprises the thinly-bedded marly micritic limestones of the 'Wellenkalk' which make up the majority of the Member, and the second facies is represented by coarser calcarenites and fossil-banks. These are interbedded with the 'Wellen-kalk' at distinct horizons which are variously named the 'Oolithkalk', 'Terebratelkalk' and the 'Schaumkalk'. Similar facies are recognised in Poland (Senkowiczowa 1957, 1961), in East Germany (Althen *et al.* 1980, Dockter *et al.* 1980) and in the type area of north Germany (Gall *et al.* 1977, Ritzkowski 1978). Both facies were developed under shallow open-marine conditions as evidenced by both the macro-fauna (including marine fish) and the microplankton (Backhaus 1971, Geiger and Hopping 1968, Ritzkowski 1978, Sellwood 1978, Senkowiczowa 1961). The limited number of different species present indicates a high environmental stress, reflecting the enclosed nature of the Germanic Basin (Sellwood *op. cit.*). The 'Wellenkalk' facies has been interpreted as forming under quiet marine conditions, and the calcarenite facies as representing higher-energy bars and fossil banks (Ritzkowski 1978, Paul and Franke 1977).

In eastern Holland, the 'Wellenkalk' facies is once again developed, although the calcarenite facies is almost totally absent. Interbedded with the shallow-marine marly limestones in this area are stromatolitic dolomites with desiccation cracks, indicative of intertidal conditions (de Boorder *et al.* 1985).

In the Southern North Sea area, the open marine limestones of the north German area are replaced by the interbedded dolomites and dolomitic mudstones of the Muschelkalk Dolomitic Member. However, marine

microplankton indicate that at least quasi-marine conditions did extend both into the Southern North Sea and across eastern England (Bertelsen 1980, Geiger and Hopping 1968, Warrington 1974). Marine conditions extended right to the western margin of the Germanic Basin and beyond, with the bivalve Lingula and marine microplankton present in the Anisian Colwick Formation around Nottingham (Frost *et al.* 1979, Rose and Kent 1955) and in the Worcester and Cheshire Basins (Warrington 1968, 1970a).

The regional picture is hence one of open marine conditions extending across the basin from Poland to north Germany, with more restricted marine influences present in the Southern North Sea area. It is within this regional setting that the sedimentology of the 'Staithes-20' well core is discussed. This is then related to the four-fold subdivision of the Muschelkalk Dolomitic Member which has been identified on the petrophysical logs throughout the U.K. Southern North Sea area (Chapter 3 section 16.8), and this in turn is tentatively related to the development of the different facies within the Lower Muschelkalk of the basin centre.

11.1 'Staithes-20' Well Core (encl. Well B)

The laminated and blocky facies identified in the Intermediate and Upper Röt Mudstone Members are also present in the Muschelkalk Dolomitic Member. The Member is dominated by the laminated facies.

11.1.1 Laminated Facies

The laminated facies comprises light green-grey micro-crystaline argillaceous dolomites and dark green-grey and red-brown anhydritic mudstones. The dolomites dominate the facies, and are

generally up to 5 cm thick, to a maximum of 15 cm. They vary from relatively silt-free to very silty.

The facies contains many features indicative of subaqueous deposition; the bases of the individual dolomites are generally sharp and frequently show load-structures (Plate 3.14); the tops may grade into the overlying mudstones, and are occasionally ripple-marked; and internally, the dolomites contain parallel and small-scale cross-lamination. Water-escape structures are also observed (Plate 3.18). Desiccation cracks occur within the facies, but these are rare and generally start at the base of a blocky facies unit above (Plate 3.16).

Displacive nodular anhydrite is common in the mudstones in the facies (Plate 3.13). This may reflect brief periods of emergence and anhydrite precipitation in a sabkha setting, or it could have formed interstitially within the sediment in a subaqueous setting (as reviewed in Kendall 1979b). The association of this nodular anhydrite with the laminated dolomites in sequences where neither desiccation cracks nor the blocky facies are obviously developed, tends to argue for a subaqueous origin. However, the overlying buckled layers are frequently eroded flat a few centimetres above the nodules, a feature which would be more likely on the deflation sabkha surface than in a subaqueous basin with relatively low current activity. The origin of these nodules remains unresolved.

11.1.2 Blocky Facies

This facies is quite rare in the Muschelkalk Dolomitic Member. It comprises red-brown silty dolomitic mudstones which are generally massive and unlaminated (Plate 3.17), or show highly brecciated lamination (Plate 3.19). Nodular anhydrite is commonly dispersed through-

out the facies, and occasionally nodules coalesce upwards to form anhydrite beds (Plate 3.15). Desiccation cracks, up to 10 cm in length, occur within the facies, and extend down into the laminated facies.

The facies is interpreted as forming in a subaerial environment. Most conclusive is the coalescing upwards of anhydrite nodules to form the chicken-wire fabric indicative of supratidal evaporites. Repeated wetting and drying of the sabkha/playa surface, resulting in repeated desiccation may once again have produced the brecciated zones within the facies.

11.1.3 Vertical Subdivision of the Member

As noted in Chapter 3 section 16.8, the Muschelkalk Dolomitic Member can be subdivided vertically into four units, based on the petrophysical logs, which are recognisable over most of the Southern North Sea area (figs. 3.15, 3.16). This subdivision is not immediately obvious in the 'Staithes-20' well core, but can be identified by linking the core to the petrophysical logs (encl. Well B). In this way the differing depositional environments of the four units can be determined.

Unit 1, the basal 'marker' of the Muschelkalk Dolomitic Member, is composed entirely of the laminated facies (Plate 3.12). Possible desiccation cracks are present at one horizon in the unit, and displacive anhydrite nodules occur within the facies (Plate 3.13). These may reflect periods of subaerial exposure, but the absence of a blocky facies development indicates that such periods, if they existed at all, were not long sustained. Unit 1 was hence dominantly subaqueously deposited.

Unit 2 shows a development similar to that seen in the Intermediate/Upper Röt Mudstone Members. Both the laminated and blocky facies are developed, the latter including both brecciated mudstones and

nodular sabkha anhydrites (Plate 3.15). Desiccation cracks are particularly common in this unit (Plate 3.16). Deposition of this unit hence occurred under alternating subaqueous and subaerial conditions.

Unit 3, which forms the majority of the Member, is dominated by the laminated facies, and hence was primarily deposited in a subaqueous environment. Periods of subaerial exposure, as indicated by the occasional development of the blocky facies (Plate 3.17) and desiccation cracks, do occur, but these are rare.

Unit 4 is composed mainly of the blocky facies. The laminated facies is present at the base of the unit, but this passes upwards through a disrupted horizon (Plate 3.19) into a generally unlaminated mudstone. This unit hence reflects a shallowing upwards from subaqueous to subaerial conditions.

11.2 Basinwide Deposition

11.2.1 Southern North Sea Area

This four-fold subdivision of the Member can be identified on the petrophysical logs throughout most of the U.K. Southern North Sea area. Hence the water depth fluctuations identified in the 'Staithes-20' well core reflect variations occurring across the whole area. Micro-plankton present in the Member in the U.K. Southern North Sea area indicate the marine origin of the subaqueous units (Geiger and Hopping 1968, Warrington 1974).

The lateral continuity of Unit 1 reflects the establishment of continuous marine conditions over most of the U.K. Southern North Sea area following the fluctuating subaerial/subaqueous conditions of the Main Röt Mudstone Member. These marine conditions did not extend into the

southern part of Quadrant 53, where this unit is not developed (Chapter 3 section 16.8, and fig. 6.1). Presumably in this area, alternating playa mudflat and lagoonal conditions continued from the Main Röt Mudstone Member.

In Unit 2, a regional regression resulted in the progradation of fluctuating subaerial/subaqueous conditions across the whole of the U.K. Southern North Sea area. In the area where Unit 1 is absent, these conditions continued without break from the Main Röt Mudstone Member.

A further, more sustained, transgression re-established marine conditions across the U.K. Sector during the deposition of Unit 3. This unit, which extends right to the basin margin in Quadrant 53 (fig. 6.1), reflects the main transgressive phase of the Muschelkalk. Occasional regressive intervals resulted in subaerial exposure (at least in the Staithes area), but this unit, which forms the majority of the Muschelkalk Dolomitic Member, was deposited primarily under sustained subaqueous conditions.

Unit 4 reflects a final regression at the top of the Muschelkalk Dolomitic Member, with the re-establishment of mainly subaerial conditions across the U.K. Southern North Sea area.

Halite beds are developed in the Muschelkalk Dolomitic Member in two (or possibly three) wells in the U.K. Southern North Sea (fig. 3.17). They have not been observed in this Member in any other wells in the study area (encl. Map 14). The halites are developed at different horizons within each well, but are restricted to Units 1 and 3.

The halite beds hence formed in separate isolated evaporitic basins, but always associated with periods of marine transgression (Units 1 and 3). They are frequently developed at the base of these transgressive units (at the base of Units 1 and 3 in well 43/17-1, and at the

base of Unit 3 in well 43/21-1) and hence probably represent the evaporation of ponded waters in depressions on the playa mudflats during the early stages of the marine transgression. Similarly, the halite beds occurring higher in Unit 3 may have been deposited during the early stages of the transgressions which followed the brief periods of subaerial deposition. Why these local depressions should occur only in the area of these two wells remains a complete mystery.

11.2.2 Basin Centre

The sea-level fluctuations which are observed towards the margin of the marine basin in the Southern North Sea area, are much less obvious in the continuous marine deposits of the basin centre. A log correlation has been made between the Dutch Sector and the north German area by NAM/RGD (1980). Based on this (fig. 6.10), it appears that Units 1 and 2 equate with the Unterer Wellenkalk below the Oolithbänke, Unit 3 with the sequence between this and the Schaumkalkbänke, and Unit 4 with the remainder of the Oberer Wellenkalk. This correlation fits with the transgressions/regressions observed in the U.K. Sector, especially in transgressive Unit 3, where the development of sustained and extensive marine conditions in the Southern North Sea area, coincides with the development of major high-energy open-marine calcarenite facies in the basin centre.

12. MUSCHELKALK HALITE MEMBER

The Muschelkalk Halite Member shows a similar development to that of the Main Röt Halite Member, with thick halites (occasionally dolomitic/anhydritic) interbedded with thin mudstones (encl. Well A). The

thickness of the Member in the U.K. Sector is also comparable to that of the Main Röt Halite Member, although its lateral extent is slightly less (compare encl. Maps 15 and 5). The Muschelkalk Halite Member shows similar log profiles and thickness throughout the study area (compare encl. Wells A and M). Further east, in East Germany, the Member passes into cyclic alternations of dolomites, anhydrites and halites (Althen *et al.* 1980, Dockter *et al.* 1980) and these in turn pass laterally into limestones and dolomites in Poland (Senkowiczowa 1961).

The Member has previously been interpreted as a lagoonal deposit (Wolburg 1961). More recent authors have recognised the east-west lateral gradation of evaporite facies and (as with the Main Röt Halite Member) have interpreted this as the result of a lateral salinity gradient across an extensive shallow basin connected to Tethys via eastern Poland (Busson 1982, Richter-Bernberg 1972b). Alternatively, Trusheim (1971) proposed that the predominance of halites over the earlier evaporite facies, resulted in part from the dissolution of diapiric Zechstein salt in the marine waters. Ziegler,W. (1975), taking this one stage further, interpreted the Muschelkalk Halite Member as entirely re-precipitated Zechstein salt.

Although this re-precipitated Zechstein source has been discarded for the Main Röt Halite Member (section 6), it cannot be totally rejected for the Muschelkalk Halite Member, as Zechstein salt movements had begun by this time in the deeper parts of the Germanic Basin in north Germany (Best *et al.* 1983). There is no evidence, however, that these diapirs had become piercing during the middle Triassic.

There are no reported bromine studies in the main part of the Muschelkalk Halite Member basin, although studies do exist in the extension of the basin in southern Germany. In this area, the Member has

a complex development, with a central zone of horizontally bedded primary halite occurring between lower and upper zones of vertically banded recrystallised halite, the origin of which is highly controversial (Borchert and Muir 1964, Dellwig 1966, Dellwig and Kühn 1980, Richter-Bernberg 1980). Despite the complexity, bromine values confirm the marine origin of the primary halites (Holser and Wilgus 1981).

From a study of the log profiles of the Member between the U.K. Southern North Sea and north Germany, a model for the development of the halite basin can be suggested. The data are less conclusive than in the Main Röt Halite Member, but a similar model of halite cyclicity within an expanding then contracting basin is proposed.

Individual cycles within the Member have not been mapped out, but the thickness distribution of the Member as a whole strongly suggests a post-Triassic dissolution margin against the Cleaver Bank High and the Texel-Ijsselmeer High. The Member shows an abrupt, rather than gradual thinning towards both of these structures (encl. Map 15), e.g. varying from 62 metres to 0 metres thickness across a single licence block (wells 49/23-2 and 49/24-16 respectively).

12.1 Halite Cyclicity

Within individual wells, the Member can be subdivided into several halite units based on the presence of thin mudstone interbeds (e.g. encl. Wells A and H (U.K. Sector); encl. Well L (Dutch Sector); encl. Wells M and N (north Germany)). Particularly in the north German area, these mudstones are frequently overlain by a thin dolomitic/anhydritic unit followed by the thicker halite (encl. Well N). As in the Main Röt Halite Member, these sequences of mudstone - (dolomite/

anhydrite) - halite are considered to be individual halite cycles. The mudstones were deposited as the fine-grained background clastic sediments which, as salinity increased, were blanketed out by the deposition of dolomites/anhydrites and finally halites. K/Mg salts (high gamma-ray/low sonic values) are not recognised. Either these were not deposited, or were subsequently dissolved at the start of the next evaporite cycle. The lateral salinity gradient across the basin is reflected by the better developed dolomite/anhydrite facies in the east of the study area.

A larger number of cycles exist in this Member than in the Main Röt Halite Member, making correlation between wells much more difficult. Detailed correlation is possible locally, but this is difficult to extend over a larger area. A more general subdivision of the Member is, however, possible.

In the U.K. Sector, the Member commonly starts with one or more thin cycles, overlain by an up to 20 metre thick cycle (e.g. well 49/26-4 of fig. 3.15). A thin, up to 3 metre thick, cycle often separates this lower thick evaporite cycle from the next major (up to 25 metre thick) cycle, which commonly extends to the top of the Member (encl. Wells A and H). In some wells further thin evaporite cycles occur to the top of the Member (as in well 49/26-4, fig. 3.15). This sequence is not always clearly developed, and hence the lateral distribution of the individual cycles is unknown. The most commonly correlatable horizon is the thin evaporite cycle sandwiched between two thick cycles in the middle of the Member (marked * on encl. Wells A and H, and fig. 3.15).

This general development of the cycles appears to have a basin-wide extent. In encl. Well N from north Germany, the thin cycles at the base of the Member are represented by a 9 metre thick cycle. Above this, a lower 40 metre and an upper 24 metre thick cycle are separated by a 5

metre thick cycle. This produces a profile similar to that in many of the U.K. Sector wells (although the uppermost thin evaporite cycles are absent). In other wells (e.g. encl. Well M) this is less clear. The development of similar profiles across the study area implies that many of the individual cycles are laterally extensive and hence were deposited either in a single evaporite basin, or in large lagoons.

Several thin cycles underlie the first thick halite in the U.K. Sector (encl. Well A), whereas a single thicker cycle appears to underlie it in the Dutch and north German areas (encl. Wells L and N respectively). This may reflect initial halite precipitation in thin lagoonal cycles in the U.K. Sector. The last thin cycle in the U.K. Sector may then equate with the single thicker cycle in the Dutch and north German areas, and hence would represent the first basinwide cycle. Basinwide halite deposition was fully established to produce the first thick halite cycle, which extends throughout the study area. Unlike the lowermost cycles, the following thin halite cycle is not of lagoonal origin. Despite its thin development, this cycle is of great lateral extent, occurring throughout the study area, and hence was probably deposited within a single extensive basin. The same is also the case for the following thick halite cycle which is also recognised across the study area. Further cycles above this are present in some wells in the U.K. Sector (fig. 3.15), and in some wells towards the centre of the basin in north Germany (fig. 4 of Trusheim 1971). These latter cycles may have been deposited within a single basin of reduced lateral extent, or they may have formed in isolated lagoons in various parts of the Germanic Basin.

12.2 Depositional History

The depositional history of the Muschelkalk Halite Member appears to be very similar to that proposed for the Main Röt Halite Member, although the evidence available is far less conclusive.

The Member is composed of a series of evaporite cycles which were generally more frequent and of shorter duration (thinner) than those of the Main Röt Halite Member. Together the cycles indicate a possible expansion, followed by contraction of the area of halite deposition. The lowermost thin cycles may have been restricted to lagoons in the U.K. Sector, while the following three cycles (two major, one minor) were deposited in a single extensive basin. The final cycles, not always present, reflect either a considerably reduced size to the single halite basin, or a return to lagoonal conditions. Hence, as with the Main Röt Halite Member, there was an expansion followed by contraction of the area of halite deposition, superimposed on which, frequent minor fluctuations produced the individual cyclicity. Once again this probably reflects eustatic fluctuations within Tethys.

The general depositional setting of the Anisian Muschelkalk Halite Member is comparable with that of the Anisian halite in the Cheshire basin. Although this basin was not directly connected to the larger Muschelkalk Halite Member basin, it too contains a series of thick halite units separated by clastic beds, with a fringe of anhydritic mudstones (Audley-Charles 1970). These halites have been interpreted as forming variously from a deep-water stratified brine (Evans 1970), in shallow lakes left after marine flooding (Arthurton 1980) and in continental playa-lakes (Colter and Barr 1975). Recent bromine profiles however indicate a marine shallow-water origin for the brine (Tucker

1981). Using the model described in detail in Tucker and Cann (1986), Tucker (*op. cit.*) calculated the water-depth at the end of each cycle at a maximum of 12.5 metres.

It is not certain that the halites of the Germanic and Cheshire Basins are exact time equivalents, although this could be expected if the controls on precipitation are global eustatic fluctuations rather than local tectonics (as proposed in section 15.1).

13. MUSCHELKALK EVAPORITE MEMBER

The Muschelkalk Evaporite Member surrounds and overlies the Muschelkalk Halite Member. In the Southern North Sea area, the Member was in part deposited marginal to the halite basin, and is in part composed of collapse breccias resulting from halite dissolution associated with near-by post-Triassic uplift and erosion. The latter are not considered further here.

13.1 Basin Centre

In eastern Europe, the anhydrites, dolomites and limestones lateral to the Muschelkalk Halite Member are of marine origin, containing an impoverished Tethyan fauna which gradually becomes extinct towards the west as the salinity increases (Senkowiczowa 1961, Ziegler,P. 1982a). In western Europe, the marine microplankton, present in both the Lower and Upper Muschelkalk, are absent from the Middle Muschelkalk succession (Geiger and Hopping 1968), although this may simply reflect hypersaline conditions, rather than a non-marine environment.

13.2 Southern North Sea Area

In the Southern North Sea area, dolomites/anhydrites and dolomitic/anhydritic mudstones fringe and immediately overlie the Muschelkalk Halite Member, both in the U.K and Dutch Sectors, and in the Danish area (Bertelsen 1980). As with the Main Röt Evaporite Member, these evaporites may have been subaqueously precipitated close to the halite basin, but probably formed supratidally further away from the halite. In the vast shallow Germanic Basin, small sea-level changes would result in transgressions and regressions over vast distances. As a result, this Member may reflect a close vertical relationship between supratidal and subtidal evaporites.

The Muschelkalk Evaporite Member not only occurs marginal to the Muschelkalk Halite Member basin, but also overlies it. Locally, beyond the Muschelkalk Halite Member basin, the evaporites which also overlie the halite can be separated from those which only occur marginal to it (fig. 3.15), producing a rough subdivision of the Member. Hence, following completion of the subaqueous halite deposition in the basin centre, a regional regression occurred, during which the sabkhas that had previously fringed the halite basin prograded out across the centre of the basin in the Southern North Sea area.

In the most marginal outcrops of eastern England, the Member equates with the Carlton Formation of Elliott (1961) (Chapter 4 section 5.2). This Formation contains massive to poorly-bedded, gypsiferous mudstones and siltstones and, in its upper part, the dolomitic sandstones of the Plains Skerry and its later equivalent the Clareborough Formation (fig. 4.11). These coarser clastics entered the Germanic Basin from the margins and gradually passed basinwards into the surrounding mudstones

and siltstones (Smith *et al.* 1973, Warrington 1968, 1974). The massive to poorly bedded Carlton Formation contrasts with the finely laminated Radcliffe Formation below (Elliott 1961), reflecting the change from the subaqueously deposited Muschelkalk Dolomitic Member equivalent, to the supratidally deposited Muschelkalk Evaporite Member equivalent.

The Carlton Formation is divided into an Upper and a Lower part, which roughly equates with the subdivision of the Muschelkalk Evaporite Member described above. The coarse clastics of the Plains Skerry and the Clareborough Formation, occur in the Upper Carlton Formation, and hence were deposited as basin-margin sands at the time of a basinwide regression, when sabkhas prograded out across the basin centre.

13.3 'Staithes-20' Well Core

The Muschelkalk Evaporite Member is present in the cored 'Staithes-20' well (encl. Well B), which lies some 50 km from the Muschelkalk Halite Member basin. In this area, the upper part of the Member is difficult to distinguish from the Muschelkalk Mudstone Member into which it passes laterally (Chapter 3 section 18.6.2).

The Member comprises green-grey mottled dolomites, light grey nodular to enterolithic anhydrite and red-brown dolomitic mudstones (Plates 3.20 and 3.21). Horizontal lamination, indicative of subaqueous deposition, is almost totally absent from the Member.

The features seen in the core are comparable with those reported from sabkha sequences elsewhere (Ali and West 1983, Kendall 1979a). The irregular-bedded dolomites (Plate 3.20), disrupted by anhydrite growth, probably formed in inter- to supratidal conditions.

Kendall (*op. cit.*) recorded disrupted dolomitic algal-mats from such an environment, although there is no direct evidence for a stromatolitic origin of the dolomites within the Muschelkalk Evaporite Member. Most conclusive evidence for the sabkha origin of the Member is the development of nodular to entrolithic anhydrite (Plate 3.21), comparable with that described from the modern-day siliciclastic sabkhas of northern Egypt (Ali and West 1983).

14. MUSCHELKALK MUDSTONE MEMBER

The Muschelkalk Mudstone Member and the Upper Muschelkalk of north Germany are not synonymous, as the former also equates with that part of the Middle Muschelkalk above the Muschelkalk Evaporite Member (Chapter 3 section 19.9). The open-marine conditions which produced the Upper Muschelkalk limestones in the centre and east of the basin did not reach the Southern North Sea area. As a result, the playa mudstone deposition which immediately followed the sabkhas of the Muschelkalk Evaporite Member in the latter area, continued synchronously with the open-marine deposition of the Upper Muschelkalk in the basin centre.

14.1 Upper Muschelkalk of the Basin Centre

Open-marine conditions returned to the majority of the Germanic Basin during deposition of the Upper Muschelkalk (Ager 1970, Geiger and Hopping 1968). Unlike the earlier Members, marine access from Tethys occurred not only through the Silesian/Morovian Gates in eastern Poland, but also via the Burgundy Gate in southern Germany (Bertelsen 1980, Ziegler,P. 1975a, b, 1982a). As a result, the basin showed much greater

open-marine influences; firstly in the formation of a high-energy bioclastic basal sequence, the Trochitenkalk, which occurs throughout the area from Poland to north Germany (Althen *et al.* 1980, Duchrow 1968, Senkowiczowa 1961); and secondly in the diverse marine fauna of the overlying Ceratitenschichten, which includes, as the name suggests, the ceratitic ammonoids which form the zone fossils (Ager 1970, Duchrow *op. cit.*, Schröder 1982). The greater through-flow of marine waters in the basin is also seen in the large number of thin bioclastic coquinas which occur within the Ceratitenschichten throughout the basin, and which Aigner (1985) has interpreted as storm-lag or tempestite deposits.

14.2 Southern North Sea area

The development of the Member is quite different in the Southern North Sea area. The bioclastic and micritic limestones of the centre and east of the basin are replaced by red-brown and green-grey anhydritic mudstones and dolomitic limestones in the Danish Sector (Bertelsen 1980), and further west, in the U.K. Southern North Sea area, by generally non-dolomitic red-brown silty, anhydritic mudstones which contain marine microplankton (Geiger and Hopping 1968).

In the Nottingham area, the Member equates with the lower part of the Harlequin Formation (Chapter 4 section 5.2.4). Marine microplankton are in general reported from this part of the Mercia Mudstone Group by Warrington (1981), implying marine influences in this Formation. Further north, where the Mercia Mudstone Group has not previously been subdivided, it is impossible to tie the reported sedimentology specifically to the Muschelkalk Mudstone Member.

14.3 'Staithes-20' Well Core (encl. Well B)

Three facies are identified in the core, the laminated and blocky facies of the previous Members, and a light brown mottled mudstone facies. As a whole, the core is much softer and less indurated than the lower mudstone Members, resulting from the much less dolomitic nature of the mudstones.

14.3.1 Laminated Facies

This facies comprises thin green-grey argillaceous dolomites with interlaminated green-grey and red-brown mudstone. The dolomites are laminated and occasionally show small-scale cross-lamination. As in previous Members, this facies is interpreted as having been deposited under subaqueous conditions. This facies is rare in the Member.

14.3.2 Blocky Facies

This comprises red-brown generally massive mudstones. Nodular anhydrite is common and occasionally coalesces to form a chicken-wire fabric (Plate 3.24). Desiccation cracks extend down from this facies, penetrating both the laminated dolomites and mottled mudstone facies. Once again, this facies is interpreted as having formed in a subaerial environment, varying from playa mudflats to siliciclastic sabkhas.

14.3.3 Mottled Mudstone Facies

This facies comprises a light brown mottled mudstone, which does not show any obvious lamination (Plate 3.23). Like the red-brown blocky mudstone facies, it is soft and impossible to thin-section successfully. The facies is almost always disrupted by vertical and

horizontal fissures filled with red-brown mudstone, and commonly passes upwards through an increasingly fissured zone into the blocky facies (Plate 3.22). The origin of this facies is unknown. It may be the result of a diagenetic/pedogenic process which produced silty/anhydritic mudstone that has subsequently been fractured by desiccation. The significant feature for this thesis is that it shows no evidence of being subaqueously deposited.

14.3.4 Depositional Model

Evidence of subaqueous deposition is restricted to the laminated facies, which is rarely developed in the Muschelkalk Mudstone Member. The blocky facies (and probably the mottled mudstone facies) formed under subaerial conditions. The Member is hence dominated by subaerial deposition, with only occasional periods of subaqueous deposition.

14.4 Basinwide Development

At first sight, this dominantly subaerial origin for the majority of the Member is in direct contradiction with the presence of marine microplankton, reported in the U.K. Southern North Sea by Geiger and Hopping (1968) and from the lower Mercia Mudstone Group (which includes this Member) by Warrington (1981). However, Smith and Warrington (1971) and Visscher (1966) have both noted that middle Triassic assemblages are only preserved in the non-oxidised green-grey units. In the Muschelkalk Mudstone Member these coincide with the subaqueously deposited laminated facies; it is thus not surprising that the palaeontology indicates a marine origin for the Member.

The development of a high-energy open marine facies in the basin centre led Ager (1970) to propose that the Upper Muschelkalk represented the most strongly transgressive phase within the Muschelkalk, and that this resulted in marine conditions extending to the U.K. area. This is not the case. The higher-energy facies reflect a greater degree of circulation in the basin, due to the additional opening of the Burgundy Gate in southern Germany, and are not the result of a more transgressive phase. Although restricted-marine conditions dominated on the East Midlands Shelf during Muschelkalk Dolomitic Member deposition, they rarely reached this area during Muschelkalk Mudstone Member deposition.

How far west from the basin centre marine conditions dominated in the Upper Muschelkalk is uncertain. Probably the whole Southern North Sea area fluctuated between subaerial and subaqueous conditions (as in the Main Röt Mudstone Member), with marine influences increasing towards the east.

14.5 Dowsing Dolomitic Formation/Dudgeon Saliferous Formation (Muschelkalk/Keuper) Boundary

While the base of the Dowsing Dolomitic Formation is clearly marked by a sequence boundary, the top of the Dowsing Dolomitic Formation, which marks the start of the upper Triassic regressive phase, is less clear. In the basin centre, the boundary is marked by a change from the marine limestones of the Upper Muschelkalk, to the fluvial/coastal-plain clastics of the Lower Keuper (Bertelsen 1980, Geiger and Hopping 1968). Based on the Ceratite zonation, the boundary is seen to be diachronous across East Germany and north Germany, with Keuper deposition advancing towards the south-west (Althen *et al.* 1980, Gall *et al.* 1977,

Schröder 1982, Wifel and Wifel 1980), following the closure of the Silesian and Morovian Gates. (Marine access to the Germanic Basin in the Keuper was restricted to the Burgundy Gate (Bertelsen 1980).)

In the Southern North Sea area, the top of the Muschelkalk Mudstone Member is defined by the 'sonic log marker' which occurs at the base of the Dudgeon Saliferous Formation throughout the U.K. Southern North Sea (Chapter 3 section 19.6.2). This 'marker' shows a similar Δt response to that seen in Units 2 and 4 of the Muschelkalk Dolomitic Member which, in the 'Staithes-20' core, are seen to be regressive units. In keeping with the basinwide end-Muschelkalk regression, the 'sonic log marker' probably also reflects a regressive change from the fluctuating subaqueous/subaerial conditions of the Muschelkalk Mudstone Member to the subaerial deposition of the lowermost Dudgeon Saliferous Formation. It is not a 'transgressive clay' as proposed by Brennand (1975).

In the more marginal Staithes area, the Dowsing Dolomitic Formation/Dudgeon Saliferous Formation boundary cannot be identified from the logs or core. A tentative boundary is defined, based on the correlation from wells further into the basin, but this is artificial, as similar subaerial deposits dominate both above and below the boundary. The top of the Dowsing Dolomitic Formation is hence unrecognisable in this most marginal area.

15. RESUMÉ OF TRANSGRESSIONS AND REGRESSIONS WITHIN THE GERMANIC BASIN

The concept of the middle Triassic transgressive phase is somewhat over simplistic: The middle Triassic does indeed represent a transgressive period of marine to playa mudflat deposition sandwiched between fluvial sediments below and fluvio-deltaic sediments above, but

internally this is composed of several transgressive and regressive cycles (fig. 6.11).

The first transgressive phase started with the Solling Mudstone Member and culminated in the Lower Röt Mudstone Member. Following the basinwide regression which produced the Hardegsen unconformity, sedimentation returned to the Germanic Basin with the deposition of the Solling Mudstone Member. In this initial stage of the transgression, sedimentation was restricted to fluvio-lacustrine deposition in the centre of the Germanic Basin, while other areas, like the Anglo-Dutch Basin and the East Midlands Shelf, remained areas of non-deposition (or even erosion). The Riff Sandstone Member represents a marginal clastic (?deltaic) sequence which entered the basin from the Broad Fourteens Basin margin. The transgression culminated in the deposition of the Lower Röt Mudstone Member. Over much of the basin centre, this Member showed the first marine influences to enter the basin. In the Southern North Sea area, where the marine origin of the Member has not been proved, it transgressed beyond the Broad Fourteens Basin margin to form the lowermost Member of the Dowsing Dolomitic Formation across both the Anglo-Dutch Basin and the East Midlands Shelf. The same may also be the case towards the basin margins in the Danish and Polish areas.

The overlying sequence up to the top of the Intermediate Röt Mudstone Member represents a somewhat complex regressive phase. Following the Lower Röt Mudstone Member, the influx of marine waters into the Germanic Basin, via eastern Poland, became restricted, and salinities increased resulting in the deposition of the Main Röt Halite Member. A transgression and then regression is seen within this Member, with the halite basin expanding from Cycle A to Cycle C and then contracting during Cycles D and E. As the regression continued, the sabkhas which had

fringed the halite basin (the Main Röt Evaporite Member) prograded out across the whole basin. These in turn were followed by the cyclic playa sequences of the Intermediate Röt Mudstone Member, in which marine-sourced lagoonal deposits were interbedded with playa mudstones. With continued regression, the lagoonal deposition became increasingly rare towards the top of this Member.

Following the Intermediate Röt Mudstone Member, there was an abrupt transgression followed by a gradual regression through to the Upper Röt Mudstone Member. As a result of the abrupt transgression, hypersaline marine conditions returned to much of the Germanic Basin, with the deposition of the Upper Röt Halite Member. Fringing the halite basin, the sabkhas of the Upper Röt Evaporite Member formed, while further from the halite basin, playa mudflat deposition continued from the Intermediate Röt Mudstone Member. During the subsequent regressive phase, this sabkha and playa mudflat deposition gradually prograded across the centre of the basin. Initially a thin sabkha sequence of the Upper Röt Evaporite Member extended across the basin centre, and this in turn was followed by the playa mudstones of the Upper Röt Mudstone Member.

Playa mudflat deposition dominated the lower part of the Upper Röt Mudstone Member, however, upwards the number of lagoonal interbeds gradually increases. This gradual transgression in the upper part of the Member occurred over much of the Germanic Basin, with marine influences increasing upwards towards the Muschelkalk in both Poland and north Germany. The upper part of the Member hence heralded the major transgression which resulted in the deposition of the overlying Muschelkalk Dolomitic Member.

The Muschelkalk Dolomitic Member reflects a transgressive,

followed by a regressive phase. The initial transgression (Unit 1) resulted in the establishment of open to restricted-marine conditions across the majority of the Germanic Basin, although towards the margins (in Quadrant 53) playa mudstone deposition continued. This was followed by a brief regressive phase (Unit 2), during which playa/lagoonal mudstones prograded across the basin in the U.K. Southern North Sea area. The major transgressive phase of the Muschelkalk Dolomitic Member is represented by Unit 3. In the basin centre, high-energy calcarenite bars were deposited, while in the Southern North Sea area, restricted marine deposition once again dominated. It is probably this second, major transgressive phase within the Member, which overstepped the southern Germanic Basin margin in the Dutch and U.K. Sectors, and which in the Nottingham area established the first middle Triassic link between the Germanic Basin and the Worcester Basin. The Muschelkalk Dolomitic Member ended with a brief regressive phase (Unit 4), during which playa mudflat/ lagoonal deposition was once more established in the U.K. Sector.

In the Southern North Sea area, following a return to the hypersaline-marine conditions of the Muschelkalk Halite Member, the remainder of the Dowsing Dolomitic Formation was deposited during a single regressive phase. A brief transgressive phase resulted first in the hypersaline lagoonal(?) deposition of the lower cycles of the Muschelkalk Halite Member, followed by the deposition of the majority of the Member in a single extensive hypersaline marine basin. The regressive phase started in the upper part of the Muschelkalk Halite Member, when deposition was once more restricted to either a reduced single halite basin, or to isolated hypersaline lagoons.

As the regression continued, the sabkhas which had fringed the Muschelkalk Halite Member basin (the Muschelkalk Evaporite Member)

prograded out across the basin, and these in turn were followed by the playa mudstones of the Muschelkalk Mudstone Member. In the basin centre, the open-marine conditions of the Upper Muschelkalk were re-established during Muschelkalk Mudstone Member deposition. These may reflect a transgressive phase in the basin, but this is not observed in the Southern North Sea area. A preferred interpretation is that the open-marine conditions resulted not from a basinwide transgression, but from the opening of the Burgundy Gate in southern Germany, which allowed greater marine access to the centre of the basin but had limited effect in the Southern North Sea area.

The culmination of the regression was the establishment, in the Lower Keuper (Dudgeon Saliferous Formation), of subaerial playa mudflat to fluvio-deltaic conditions across the whole basin.

15.1 Origin of the Transgressions/Regressions

The small-scale water-depth fluctuations within individual Members may have resulted from a variety of causes, including local tectonics within the basin, reef growth/tectonics at the basin entrance, or sea-level fluctuations within Tethys. The larger scale cyclicity is, however, assumed to have been of eustatic origin.

This interpretation is based on a comparison between the major sea-level fluctuations within the Germanic Basin, and the global coastal onlap charts of Haq *et al.* (1987), which were produced from sections in Svalbard, on the arctic island of Bjørnøya, in the Dolomites of Italy, and from the Salt Range in Pakistan. The only directly correlatable horizons are the late Skythian/Anisian and the Anisian/Ladinian boundaries, but within this framework there is a close comparison between

the third-order onlap cycles and the sea-level fluctuations within the Germanic Basin (fig. 6.11).

Within the late Skythian, two third-order regressive cycles occur (numbers 1.3 and 1.4 (Haq *et al.*(*op. cit.*)). These coincide with the regressive phases from the Lower Röt Mudstone Member to the Intermediate Röt Mudstone Member, and from the Upper Röt Halite Member to the Upper Röt Mudstone Member. In the Anisian three regressive cycles occur, the last of which continues through into the Ladinian (Haq *et al.*(*op. cit.*)). The lower two of these cycles (numbers 1.5 and 2.1) probably equate with the Muschelkalk Dolomitic Member, while the final cycle (number 2.2.) equates with the Muschelkalk Halite Member to Lower Keuper regressive phase. It is interesting to note that the major transgression of Muschelkalk Dolomitic Member Unit 3 appears to coincide with the boundary between two second-order cycles. Also there is no basal Ladinian transgression to explain the formation of the Upper Muschelkalk.

The sea-level fluctuations within the Germanic Basin are hence related to eustatic fluctuations outside of this basin. The origin of this 1 to 5 m.y. cyclicity is problematical. Glaciation offers the only known mechanism for eustatic sea-level changes on the 1 to 10 m.y. time-scale (Schlanger 1986, Summerhayes 1986), yet in the Triassic, polar ice-caps were absent (Parrish *et al.* 1982).

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APPENDICES

LIST OF APPENDICES

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APPENDIX A

TABULATION OF WELL LOG DATA

This appendix contains a listing of all the wells examined in the study area and the thickness of the various Members in each. This data forms the basis of the enclosed isopach maps (encl. Maps 1 - 16).

Table 1 contains data on Members up to and including the Main Röt Mudstone Member. This table also contains the thicknesses for the basinwide subdivisions of the Main Röt Halite Member .

Table 2 contains thickness data for the Members from the Muschelkalk Dolomitic Member to the Muschelkalk Mudstone Member plus the total Dowsing Dolomitic Formation thickness (for the same wells as Table 1). Also included in this table are the depths below sea-level to the top Dowsing Dolomitic Formation and top Bunter Sandstone Formation. The operator of each well, along with information on unconformities, faults etc is given in Table 2.

In both tables, thicknesses and depths refer to the Members as defined in this thesis for the U.K. Southern North Sea, and their lateral lithostratigraphic equivalents in the remainder of the study area.

The Codes and Abbreviations used in the tables are explained in a Key which follows Table 2.

APPENDIX A - TABLE 1

Well Name	SMM	RSM	LRMM	MRHM	.....MRHM cycles..... a	b	c	d	e	f	MREM	IRMM	URHM	UREM	URMM	MRMM
ONSHORE U.K.																
Axholm 1	OS	OS	5,8	0,0	-	-	-	-	-	-	7,9	,cannot be subdivided,				48,8
Bardney 1	OS	OS	OS	0,0	-	-	-	-	-	-	8,0	,cannot be subdivided,				56,0
Barton 1	OS	OS	7,6	0,0	-	-	-	-	-	-	7,5	10,0	0,0	3,7	29,0	39,0
Burton-on -Stather 1	OS	OS	8,5	0,0	-	-	-	-	-	-	17,0	14,0	0,0	5,0	30,5	44,5
Corringham 8	OS	OS	3,0	0,0	-	-	-	-	-	-	8,0	,cannot be subdivided,				51,0
Cropwell Bishop 1	OS	OS	OS	MF	-	-	-	-	-	-	MF	,cannot be subdivided,				MF
Cropwell Butler 1	OS	OS	OS	MF	-	-	-	-	-	-	MF	,cannot be subdivided,				MF
Glentworth 4	OS	OS	4,0	0,0	-	-	-	-	-	-	9,5	,cannot be subdivided,				53,0
Harlequin 1	OS	OS	OS	MF	-	-	-	-	-	-	MF	,cannot be subdivided,				MF
Hornsea 1	OS	OS	10,0	0,0	-	-	-	-	3,0*	5,5*	13,4	14,5	0,0	4,5	46,0	60,5
Hunmanby 1	OS	OS	11,0	27,5	0,0	6,5	15,0	6,0	4,5*	5,5*	10,0	14,5	0,0	4,0	36,5	51,0
Hunstanton 1	OS	OS	OS	0,0	-	-	-	-	-	-	3,3	,cannot be subdivided,				39,9
Langar 1	OS	OS	OS	MF	-	-	-	-	-	-	MF	,cannot be subdivided,				MF
Locton 7	OS	OS	9,8	42,7	0,0	11,0	10,5	21,0	?	?	12,2	13,0	0,0	3,7	31,7	44,7
Nettleton 1	OS	OS	4,6	0,0	-	-	-	-	-	-	8,8	,cannot be subdivided,				53,3
Nocton 7	OS	OS	OS?	0,0	-	-	-	-	-	-	10,5	,cannot be subdivided,				57,0
North Dalton 1	OS	OS	11,0	0,0	-	-	-	-	3,0*	7,5*	15,5	11,6	0,0	4,0	37,8	49,4
Plungar 12	OS	OS	OS	MF	-	-	-	-	-	-	MF	,cannot be subdivided,				MF
Redmile 1	OS	OS	OS	MF	-	-	-	-	-	-	MF	,cannot be subdivided,				MF
Ruskington 1	OS	OS	OS	0,0	-	-	-	-	-	-	?	,cannot be subdivided,				57,0
Saxthorpe 1	OS	OS	OS	OS	-	-	-	-	-	-	OS	,cannot be subdivided				32,6
Sibsey 1	OS	OS	OS	0,0	-	-	-	-	-	-	11,6?	,cannot be subdivided,				53,0?
Somerton 1	OS	OS	OS	MF	-	-	-	-	-	-	MF	,cannot be subdivided,				MF
South Cliffe 1	OS	OS	9,8	0,0	-	-	-	-	3,0*	9,5*	18,0	12,0	0,0	5,0	34,0	46,0
South Creake 1	OS	OS	OS	0,0	-	-	-	-	-	-	7,9	,cannot be subdivided,				32,3
STAITHES S20	OS	OS	5,8	0,0	.....collapse breccia.....						11,6	17,0	0,0	3,0	28,9	46,0
Tetney Lock 1	OS	OS	7,4	0,0	-	-	-	-	-	-	8,2	,cannot be subdivided,				56,0
Torksey 4	OS	OS	<2,0	0,0	-	-	-	-	-	-	7,1	,cannot be subdivided,				51,8
Welton 1	OS	OS	3,5?	0,0	-	-	-	-	-	-	10,0	,cannot be subdivided,				54,0
U.K. NORTH SEA																
36/23-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
36/26-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
37/23-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
38/16-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
38/18-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
38/22-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U

Well Name	SMM	RSM	LRMM	MRHM	a	b	c	d	e	f	MREM	IRMM	URHM	UREM	URMM	MRMM

Thickness of Members in metres. For Abbreviations see KEY at end of Table 2

APPENDIX A - TABLE 1 (continued)

Well Name	SMM	RSM	LRMM	MRHM	.....MRHM cycles..... a	b	c	d	e	f	MREM	IRMM	URHM	UREM	URMM	MRMM
38/25-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
38/29-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
41/ 8-1	OS	OS	8,2	0,0	-	-	-	-	-	-	12,2	,cannot be subdivided,				46,0
41/20-1	OS	OS	7,0	47,2	0,0	14,5	20,0	13,5	4,0*	8,0*	11,9	17,7	8,5	2,1	49,7	67,4
41/24-1	OS	OS	6,4	17,4	?	?	?	?	5,0*	7,5*	12,8	16,2	4,5	2,5	35,0	51,3
42/13-1	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
42/14-1	OS	OS	11,3	37,5	0,0	2,0*	18,0	18,0	4,0*	6,0*	12,2	15,2	0,0	3,0	43,0	58,2
42/23-1	OS	OS	9,8	61,5	2,0*	19,5	16,0	21,0	3,5	8,5*	9,0	18,3	6,0	2,5	53,0	71,3
42/26-1	OS	OS	9,8	0,0	-	-	-	-	-	-	7,9	,cannot be subdivided,				+50,0
42/28-1	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
42/28-2	OS	OS	9,5	38,4	5,0*	8,0	11,0	11,0	5,0	5,5*	5,6	16,2	5,5	8,5	45,5	61,7
42/29-1	OS	OS	10,1	65,0	5,5	16,5	18,0	19,0	6,0	6,0*	6,0	17,7	8,8	2,5	55,0	72,7
42/30-1	OS	OS	11,0	71,0	5,0	19,5	18,0	25,0	4,0	7,0*	7,0	20,0	9,5	2,5	73,0	93,0
43/ 3-1	12,2	5,8	13,4	18,0	0,0	7,5	7,0	3,0	3,5*	3,0*	6,7	22,0	0,0	4,0	51,5	73,5
43/ 7-1	6,7	3,0	9,4	0,0	-	-	-	-	-	-	10,4	14,5	0,0	4,0	42,0	56,5
43/ 8-1	11,3	5,8	13,1	59,1	5,0	19,0	21,0	16,0	5,5*	5,0*	10,4	18,6	6,7	2,0	63,4	82,0
43/ 8-2	10,4	6,4	14,3	56,4	6,0	19,0	20,0	12,0	?	?	13,1?	17,3	0,0	6,5	61,0	78,4
43/11-1	2,7	3,0	10,0	9,0	1,0*	5,0*	9,0	3,0*	4,5*	?	5,4	22,5	0,0	3,5	46,0	68,5
43/16-1	OS	OS	10,4	64,6	7,0	19,0	18,0	19,0	2,0	5,8*	12,2	18,0	5,6	2,2	56,0	74,0
43/17-1	OS	OS	10,1	60,7	7,0	15,0	20,0	19,0	6,0*	3,0*	9,8	18,5	5,5	2,0	50,0	68,5
43/20-1	10,7	4,3	16,5	71,5	16,0	18,0	19,0	18,0	grades to IRMM			28,3	8,8	2,7	78,9	107,2
43/21-1	OS	OS	11,6	66,0	3,0	19,0	17,5	20,0	6,0	6,0*	6,0	20,0	9,6	2,5	61,0	81,0
43/30-1	OS	OS	9,1	45,0	1,5*	10,0	12,0	15,5	5,5	6,0*	6,0	15,5	5,5	1,5	66,0	81,5
44/ 2-1	21,6	2,4	13,1	14,6	0,0	5,0	9,5	,,grades to IRMM,,				23,2	0,0	5,8	59,1	82,3
44/ 7-1	21,0?	3,0?	22,9?	0,0	-	-	-	-	-	-	12,2	15,0	0,0	3,0	+5,0	+20,0
44/14-1	22,6?	1,2?	20,7?	0,0	-	-	-	-	-	-	22,9	19,8	0,0	5,2	+61,6	+81,4
44/19-2	18,6?	1,8?	22,3?	63,5	6,0	15,0	21,0	21,0	5,0*	4,5*	10,0	19,5	0,0	6,5	79,5	99,0
44/21-1	OS	OS	9,1	67,0	2,0	17,0	22,0	18,0	8,0	6,0*	6,0	18,2	10,5	3,0	74,0	92,2
44/23-1	8,2	1,5	8,5	63,3	3,0	16,0	20,0	18,5	6,0	5,0*	5,0	17,0	5,8	1,5	67,0	84,0
44/24-1	11,6	2,7	10,1	76,0	11,0	17,5	20,5	19,5	7,5	5,0*	5,0	17,5	9,5	2,5	71,0	88,5
44/26-1	OS	OS	10,4	53,0	3,0*	6,0	18,0	18,0	7,0	6,0*	6,0	17,5	4,0	2,5	63,0	80,5
47/ 3-1	OS	OS	11,0	57,0	1,0*	11,0	17,0	23,0	4,5	6,0*	6,0	18,0	6,5	3,0	64,0	82,0
47/ 5-1	OS	OS	10,7	109,0	9,0	27,0	23,0	24,0	22,0	3,5	0,0	15,0	10,5	1,0	67,0	82,0
47/ 8-1	OS	OS	12,2	45,0	0,0	5,0	14,0	22,0	3,5	5,0*	5,0	17,0	0,0	5,0	52,0	69,0
47/ 8-2	OS	OS	11,6	44,5	0,0	1,0*	17,5	22,0	3,5	5,5*	5,5	17,0	2,5	3,5	54,0	71,0
47/ 9-1	OS	OS	11,2	84,0	20,0	13,0	17,0	20,0	6,0*	6,0*	12,0	16,0	2,5	2,5	65,0	81,0
47/ 9-2	OS	OS	10,0	41,8	0,0	7,5	16,0	19,0	4,5*	5,5*	10,2	17,0	0,0	5,0	50,0	67,0
47/ 9-3	F	F	F	+81,4	+26,0	16,0	15,0	19,0	4,5	5,5*	5,6	16,0	0,0	4,5	47,0	63,0
47/13-1	OS	OS	9,1	21,6	0,0	1,5*	13,0	8,0	5,5*	5,0*	10,4	15,0	0,0	4,0	44,0	59,0
47/13-2	OS	OS	8,8	21,0	0,0	2,0*	11,0	9,0	4,0*	5,5*	9,9	14,0	0,0	5,5	44,5	58,5
47/14-2	OS	OS	8,6	15,2	0,0	1,5*	11,0	3,0	5,0*	5,5*	10,8	16,5	0,0	4,5	43,0	59,5
47/15-1	OS	OS	8,0	0,0	-	-	-	-	-	-	11,0	,cannot be subdivided,				69,8
47/15-2	OS	OS	8,5	0,0	-	-	-	-	-	-	9,0	13,0	0,0	3,5	60,0	63,0
47/18-1	OS	OS	8,2	9,5	0,0	1,5*	8,0	3,0*	4,5*	4,0*	11,5	14,5	0,0	6,0	33,0	47,5
47/20-1	OS	OS	8,9	12,0	0,0	1,0*	12,0	5,0*	2,5*	3,5*	11,0	14,5	0,0	5,0	38,0	52,5
47/25-2	OS	OS	3,7	0,0	-	-	-	-	-	-	14,6	,cannot be subdivided,				43,6
Well Name	SMM	RSM	LRMM	MRHM	a	b	c	d	e	f	MREM	IRMM	URHM	UREM	URMM	MRMM

Thickness of Members in metres. For Abbreviations see KEY at end of Table 2

APPENDIX A - TABLE 1 (continued)

Well Name	SMM	RSM	LRMM	MRHM	,,,,,,,,MRHM cycles,,,,,,,, *a*	*b*	*c*	*d*	*e*	*f*	MREM	IRMM	URHM	UREM	URMM	MRMM
47/29-1	OS	OS	3,7	0,0	-	-	-	-	-	-	14,9	,cannot be subdivided,				39,0
48/ 3-1	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
48/ 6-2	OS	OS	11,0	54,5	1,0•	16,5	16,5	21,0	5,5•	6,0•	11,5	17,5	0,0	4,0	66,0	83,5
48/ 6-5	OS	OS	11,3	54,9	0,0	16,0	17,5	21,0	6,0•	6,0•	12,1	20,0	5,5	1,0	69,0	89,0
48/ 6-10	OS	OS	11,6	53,6	0,0	16,0	17,5	20,0	5,5•	6,5•	12,4	19,0	2,5	3,5	71,0	90,0
48/ 7-1	OS	OS	10,4	52,0	0,0	15,5	18,5	19,0	4,5•	6,0•	10,5	17,0	0,0	5,5	62,0	79,0
48/ 7-4	OS	OS	9,0	69,0	5,0	18,5	17,0	22,0	7,0	5,0•	5,0	19,0	5,8	2,0	68,0	87,0
48/10-1	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
48/11-1	OS	OS	9,2	32,3	?	?	?	?	4,5•	4,5•	8,9	14,3	0,0	4,6	+20,1	+34,4
48/11-2	OS	OS	9,1	26,9	0,0	16,0	11,0	0,0	3,0•	4,5•	7,6	13,0	0,0	4,5	38,0	51,0
48/12-1	OS	OS	8,8	62,2	3,0	19,5	16,0	20,0	4,5	6,0•	6,1	17,0	0,0	5,5	65,0	82,0
48/12-2	OS	OS	8,8	53,9	9,5	16,0	15,0	14,0	4,0•	6,0•	10,1	14,0	0,0	5,2	52,7	66,7
48/13-1	OS	OS	9,1	45,5	0,0	8,5	17,5	19,0	3,0•	4,5•	7,5	15,2	0,0	4,3	60,0	75,2
48/13-2	OS	OS	9,5	60,0	8,0	14,0	15,0	19,0	4,0	5,5•	5,5	15,0	0,0	5,5	47,5	62,5
48/17-1	OS	OS	8,8	13,5	1,0•	9,0	3,0	2,0•	3,5•	4,0•	9,5	,cannot be subdivided,				57,3
48/18-2	OS	OS	7,3	24,5	1,5•	9,5	13,5	?	?	?	10,5	,cannot be subdivided,				56,6
48/19-1	OS	OS	8,5	45,5	1,0•	11,5	11,0	22,0	3,5•	4,0•	7,5	17,5	0,0	3,0	60,0	77,5
48/20-1	OS	OS	9,1	58,5	9,5	15,5	15,0	16,0	4,0•	4,5•	8,5	18,0	0,0	4,5	57,0	75,0
48/21-2	OS	OS	6,4	0,0	-	-	-	-	-	-	16,0	,cannot be subdivided,				50,9
48/22-2	OS	OS	7,9	7,0	3,0•	5,5	?	?	?	?	9,4	,cannot be subdivided,				53,6
48/25-1	OS	OS	8,2	25,3	2,0•	5,0	14,0	5,5	3,5•	4,0•	7,7	,cannot be subdivided,				82,9
48/28-1	OS	OS	4,5	0,0	-	-	-	-	-	-	11,0	,cannot be subdivided,				42,0
48/29-5	OS	OS		0,0	-	-	-	-	-	-	10,0	,cannot be subdivided,				44,8
48/30-2	OS	OS		0,0	-	-	-	-	-	-	8,8	,cannot be subdivided,				61,8
49/ 1-1	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
49/ 2-1	OS	OS	9,1	0,0	-	-	-	-	6,0•	4,0•	13,0	?	U	U	U	+21,0
49/ 2-2	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/ 5-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/ 6-2	OS	OS	9,1	64,0	11,5	19,0	15,5	18,5	3,0•	4,5•	7,5	15,0	0,0	4,0	36,0	51,0
49/ 6-3	OS	OS	7,7	43,0	0,0	6,0	14,5	19,0	3,5	4,0•	4,0	14,0	0,0	4,0	50,0	64,0
49/ 8-1	OS	OS	9,8	0,0	-	-	-	-	-	-	7,3	+7,0	U	U	U	+7,0
49/ 9-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/10-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/11-1	OS	OS	8,5	61,0	10,0	18,0	15,5	18,0	3,5•	4,0•	7,6	14,9	0,0	4,3	55,5	70,4
49/12-1	OS	OS	7,6	48,4	0,0	15,5	15,0	17,5	3,0•	5,5•	8,6	14,5	0,0	6,0	55,5	70,0
49/13-2	OS	OS	7,9	16,0	0,0	2,0•	7,0	5,5	3,0•	5,0•	8,0	13,0	0,0	2,5	54,0	67,0
49/13-3	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/13-4	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/14-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/16-1	OS	OS	7,9	53,3	17,0	12,0	14,0	11,0	4,0•	4,0•	7,9	,cannot be subdivided,				83,2
49/17-1	OS	OS	10,7	36,5	0,0	10,0	14,5	11,5	4,0•	5,5•	9,5	,cannot be subdivided,				69,8
49/18-2	OS	OS	8,2	31,5	2,0•	5,0	13,5	11,0	4,0•	5,5•	9,5	,cannot be subdivided,				65,2
49/19-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/19-3	OS	OS	6,4	0,0	-	-	-	-	2,5•	5,0•	15,5	12,0	0,0	5,5	43,0	55,0
49/20-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/20-2	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/21-2	OS	OS	8,5	18,6	0,0	5,5	4,5	8,5	3,0•	4,5•	7,4	,cannot be subdivided,				82,9
49/21-3	OS	OS	7,9	30,5	1,5•	3,5	15,0	10,5	3,0•	4,5•	7,5	,cannot be subdivided,				89,6
49/22-2	OS	OS	8,2	43,3	13,0	9,0	14,0	9,5	4,0•	4,5•	8,7	,cannot be subdivided,				69,7
Well Name	SMM	RSM	LRMM	MRHM	*a*	*b*	*c*	*d*	*e*	*f*	MREM	IRMM	URHM	UREM	URMM	MRMM

Thickness of Members in metres, For Abbreviations see KEY at end of Table 2

APPENDIX A - TABLE 1 (continued)

Well Name	SMM	RSM	LRMM	MRHM	,,,,,,,,MRHM cycles,,,,,,,, *a*	*b*	*c*	*d*	*e*	*f*	MREM	IRMM	URHM	UREM	URMM	MRMM
49/22-3	OS	OS	8,2	33,0	7,5	6,0	14,5	5,5	2,0*	4,0*	6,0	,cannot be subdivided,				76,5
49/23-2	OS	OS	8,2	31,5	2,0*	7,0	14,5	8,5	2,0*	4,0*	6,0	,cannot be subdivided,				68,2
49/23-4	F	F	F	F	F	F	F	F	F	F	F	F	F	F	+21,0	+21,0
49/24-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/24-2	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/24-3	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/24-4	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/24-12	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/24-16	OS	OS	9,2	0,0	-	-	-	-	-	-	16,5	,cannot be subdivided,				67,7
49/25-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/25-2	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/25-3	OS	OS	7,0	0,0	-	-	-	-	-	-	+8,5	U	U	U	U	U
49/26-4	OS	OS	8,8	0,0	-	-	-	-	-	-	15,0	,cannot be subdivided,				81,0
49/27-3	OS	OS	8,5	0,0	-	-	-	-	-	-	11,9	,cannot be subdivided,				80,4
49/28-3	OS	OS	9,8	30,5	0,0	16,5	14,5	2,5*	3,5*	3,5*	7,3	,cannot be subdivided,				71,0
49/29-1	OS	OS	8,2	0,0	-	-	-	-	-	-	17,4	,cannot be subdivided,				53,0
49/30-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/30-2	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
49/30-3	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
50/26-1	OS	OS	7,9	0,0	-	-	-	-	-	-	3,4	,cannot be subdivided,				70,1
52/ 5-2	OS	OS	OS	OS	-	-	-	-	-	-	OS	OS	OS	OS	?	44,2
52/ 5-11	OS	OS	OS	OS	-	-	-	-	-	-	OS	OS	OS	OS	?	17,1
53/ 1-1	OS	OS	OS	OS?	-	-	-	-	-	-	OS?	OS?	OS?	OS?	?	67,7
53/ 1-2	OS	OS	OS	OS	-	-	-	-	-	-	OS	OS	OS	OS	?	43,0
53/ 1-3	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
53/ 2-3	OS	OS	4,3	0,0	-	-	-	-	-	-	12,0	,cannot be subdivided,				67,0
53/ 3-1	F	F	F	F	F	F	F	F	F	F	F	F	F	F	?	+9,8
53/ 4-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
53/ 4-2	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
53/ 4-3	OS	OS	4,3	0,0	-	-	-	-	-	-	9,4	,cannot be subdivided,				64,6
53/ 4-4	OS	OS	4,0	0,0	-	-	-	-	-	-	9,4	,cannot be subdivided,				63,4
53/ 5-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
53/ 7-1	OS	OS	OS	OS	-	-	-	-	-	-	OS	OS	OS	OS	?	47,9
53/ 7-2	OS	OS	OS	OS	-	-	-	-	-	-	OS	OS	OS	OS	?	49,0
53/ 8-1	OS	OS	OS	OS	-	-	-	-	-	-	OS	OS	OS	OS	?	52,1
53/10-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
53/12-1	OS	OS	OS	OS	-	-	-	-	-	-	OS	OS	OS	OS	?	27,7
53/12-3	OS	OS	OS	OS	-	-	-	-	-	-	OS	OS	OS	OS	?	12,0?
53/14-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
53/16-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
53/19-1	OS	OS	OS	OS	-	-	-	-	-	-	OS	OS	OS	OS	OS	17,0?
54/ 1-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
54/11-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
Well Name	SMM	RSM	LRMM	MRHM	*a*	*b*	*c*	*d*	*e*	*f*	MREM	IRMM	URHM	UREM	URMM	MRMM

Thickness of Members in metres, For Abbreviations see KEY at end of Table 2

APPENDIX A - TABLE 1 (continued)

Well Name	SMM	RSM	LRMM	MRHM	,,,,,,,,MRHM cycles,,,,,,,, *a*	*b*	*c*	*d*	*e*	*f*	MREM	IRMM	URHM	UREM	URMM	MRMM
DUTCH NORTH SEA																
B/17-2	24,0?	NP	8,0?	96,0	12,0	17,5	29,0	16,0	5,0*	4,0*	9,0	40,0	0,0	8,0	101,0?	141,0?
D/15-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
E/16-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
E/17-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
F/ 4-1	20,0?	2,0?	7,0?	42,0	3,5	10,5	17,0	10,0	3,5*	3,5*	7,0	20,0	0,0	7,0	53,0	73,0
F/ 7-1	+16,0?	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
F/ 9-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
F/10-1	24,0?	NP	7,0?	0,0	-	-	-	-	-	-	17,0	21,0	0,0	12,0	+27,0	+49,0
F/14-2	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
F/15-1	24,0?	NP	8,0?	50,0	3,0	13,0	14,0	18,5	8,0*	6,0*	14,0	18,0	0,0	4,0	+35,0	+53,0
G/17-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
K/ 6-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
K/ 7-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
K/ 7-2	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
K/ 8-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
K/ 9-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
K/11-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
K/11-2	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
K/12-1	12,0	2,0	9,0	60,0	16,0	11,5	18,0	16,0	2,5*	4,5*	7,0	,cannot be subdivided,				90,0
K/13-1	1,5	1,0	7,0	0,0	-	-	-	-	3,0*	3,5*	11,0	14,0	0,0	4,0	50,0	64,0
K/14-1	3,0	1,0	9,0	35,0	0,0	8,0	19,0	8,0	3,5*	3,5*	7,0	,cannot be subdivided,				77,0
K/17-1	5,0	2,0	7,0	46,0	0,0	23,5	15,0	7,0	2,0*	3,0*	5,0	,cannot be subdivided,				95,0
K/17-2	F	F	F	+11,0	?	?	?	?	2,0*	3,0*	5,0	,cannot be subdivided,				+55,0
L/ 2-1	25,0	NP	10,0	141,0	42,0	21,0	43,5	26,0	10,0	3,5*	3,5	24,0	15,0	0,0	100,0	124,0
L/ 2-2	39,0	NP	8,0	262,0	59,0	45,0	105	45,0	12,0	5,0*	5,0	24,0	0,0	8,0	100,0?	124,0?
L/ 7-1	9,0	2,0	8,0	0,0	-	-	-	-	2,5*	3,5*	10,0	,cannot be subdivided,				98,0
L/ 8-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
L/10-1	13,0	10,0	11,0	44,0	11,5	9,0	17,0	7,5	3,5*	3,5*	7,0	,cannot be subdivided,				94,0
L/10-2	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
L/10-3	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
L/10-4	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
L/10-7	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
L/11-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
L/12-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
L/13-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
M/ 7-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
M/ 9-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
N/ 4-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
P/ 2-1	2,0?	4,0?	9,0	20,0	3,5*	7,5	10,0	4,0	2,5*	3,5*	10,0	,cannot be subdivided,				97,0
P/ 5-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
Well Name	SMM	RSM	LRMM	MRHM	*a*	*b*	*c*	*d*	*e*	*f*	MREM	IRMM	URHM	UREM	URMM	MRMM

Thickness of Members in metres, For Abbreviations see KEY at end of Table 2

APPENDIX A - TABLE 1 (continued)

Well Name	SMM	RSM	LRMM	MRHM	,,,,,,,,MRHM cycles,,,,,,,, a	b	c	d	e	f	MREM	IRMM	URHM	UREM	URMM	MRMM
P/ 6-1	2,0	7,0	5,0	8,0	2,0•	4,5•	8,5	4,0•	2,5•	3,0•	18,0	,cannot be subdivided,				75,0
P/ 6-2	3,0	6,0	3,0	21,0	0,0	9,5	12,5	4,0•	3,0•	4,0•	11,0	,cannot be subdivided,				72,0
P/ 7-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
P/ 9-1	1,0	3,0	2,0	0,0	-	-	-	-	-	-	12,0	,cannot be subdivided,				71,0
P/10-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
P/12-1	2,0	6,0	5,0	0,0	-	-	-	-	-	-	7,0	,cannot be subdivided,				57,0
Q/ 1-1	8,0	2,0	12,0	0,0	-	-	-	-	-	-	16,0	,cannot be subdivided,				+31,0
Q/ 4-1	6,1	4,9	3,4	28,0	1,5•	16,0	10,5	4,5•	3,0•	3,5•	11,0	,cannot be subdivided,				68,3
Q/ 8-1	13,0	3,0	6,0	13,0	2,5•	3,5	9,5	3,0•	3,0•	4,5•	13,0	,cannot be subdivided,				75,0
Q/10-2	5,0?	4,0?	2,0?	0,0	1,5•	5,0•	4,0•	2,5•	3,0•	5,5•	22,0	,cannot be subdivided,				66,0
Q/11-1	8,0?	4,0?	3,0?	0,0	-	-	-	-	-	-	12,0	,cannot be subdivided,				77,0
ONSHORE NETHERLANDS																
Amsterdam (east)	11,0	1,0	3,0	22,0	0,0	12,0	9,5	3,0•	5,0•	3,0•	11,0	,cannot be subdivided,				112,0
Blijham-1	66,0	NP	5,0	107,0	0,0	61,0	28,0	21,5	6,0•	6,0•	12,0	21,0	14,0	0,0	105,0	126,0
Eleveld-101	61,0	NP	5,0	100,0	0,0	58,0	29,0	14,0	4,0•	6,0•	10,0	15,0	0,0	4,0	75,0	90,0
Emmen-7	84,0	NP	5,0	111,0	0,0	62,0	33,0	17,0	6,0•	8,0•	14,0	22,0	2,0	5,0	112,0	134,0
Gelderland	13,0	NP	1,0	0,0	-	-	-	-	6,0•	6,0•	30,0	,cannot be subdivided,				116,0
Hengelo-31	ND	ND	ND	58,7	0,0	36,0	21,0	?	?	?	16,3	ND	ND	ND	ND	ND
Noord Holland 1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
Noord Holland 2	16,0	2,0	4,0	0,0	-	-	-	2,0•	2,5•	5,0•	15,0	,cannot be subdivided,				99,0
Noord Holland 3	13,0	2,0	3,0	20,0	0,0	10,0	9,5	?	?	?	10,5	,cannot be subdivided,				66,0
Sleen-4	83,0	NP	5,0	68,0	0,0	23,0	31,0	15,0	5,0•	7,0•	12,0	19,0	0,0	5,0	97,0	116,0
Krabbendam	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
Vijk 5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Vijk 7	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
Vijk 13	?	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
Vijk 21	77,0	NP	6,0	39,0	0,0	16,0	22,5	?	?	?	15,0	,cannot be subdivided,				+92,0
Zuid Holland	OS?	OS?	OS?	0,0	-	-	-	-	-	-	7,0	,cannot be subdivided,				?
ONSHORE GERMANY																
Bielefeld 1	10,0	NP	?	38,0	0,0	38,0	10,0•	8,0•	-11,0•-		27,0	15,0	0,0	7,0	79,0	94,0
Bockenem 1	45,0	NP	?	128,0	0,0	83,0	30,0	17,0	-17,0•-		17,0	21,0	0,0	19,0	113,0	134,0
Eldingen	?	?	?	144,0	0,0	63,0	21,0	59,0	-23,0•-		23,0	26,0	15,0	10,0	171,0	197,0
Emlichheim Z1	97,0	NP	?	84,0	0,0	44,0	24,0	16,0	-10,0•-		10,0	23,0	0,0	3,0	105,0	128,0
Emsland	95,0	NP	6,0	73,0	0,0	40,0	22,5	11,0	4,0•	8,5•	12,0	27,0	5,0	6,0	123,0	150,0
Ems River Mouth	50,0	NP	5,0	121,0	0,0	73,0	29,0	19,0	4,5•	4,5•	9,0	17,0	0,0	8,0	64,0	81,0
Getelo Z1	106,0	NP	?	32,0	0,0	16,0	12,0	6,0	-	7,0•-	7,0	24,0	0,0	2,0	101,0	125,0
Harpstedt Z1	84,0	NP	?	109,0	0,0	67,0	27,0	16,0	-12,0•-		12,0	20,0	5,0	11,0	94,0	114,0
Kassebruch T2	98,0	NP	?	113,0	0,0?	67,0?	29,0	18,0	-15,0•-		15,0	27,0	17,0	21,0	147,0	174,0
Lieme 1	14,0	NP	?	0,0	-	-	-	-	-	-	23,0	15,0	0,0	9,0	79,0	94,0
Messingen Z1	106,0	NP	?	109,0	0,0	61,0	28,0	20,0	-23,0•-		23,0	28,0	0,0	17,0	147,0	175,0

Well Name	SMM	RSM	LRMM	MRHM	a	b	c	d	e	f	MREM	IRMM	URHM	UREM	URMM	MRMM

Thickness of Members in metres. For Abbreviations see KEY at end of Table 2

APPENDIX A - TABLE 1 (continued)

Well Name	SMM	RSM	LRMM	MRHM	,,,,,,,,*MRHM cycles*,,,,,,,, *a*	*b*	*c*	*d*	*e*	*f*	MREM	IRMM	URHM	UREM	URMM	MRMM
Nord deutschland	21,0	NP	?	134,0	9,0	69,0	28,0	24,0	-15,0*-		15,0	26,0	0,0	10,0	146,0	172,0
Ratzel T1	93,0	NP	?	0,0	-	-	-	-	-	-	19,0	,cannot be subdivided,				101,0
Rehden 8	10,0	NP	?	21,0	0,0	21,0	?	?	?	?	10,0	16,0	0,0	8,0	42,0	58,0
South Bremen	74,0	NP	7,0	122,0	0,0	75,5	29,0	19,0	4,0*	6,0*	10,0	20,0	6,0	10,0	101,0	121,0
South Hannover	98,0	NP	4,0	123,0	0,0	71,0	29,0	23,0	4,0*	9,5*	13,0	23,0	0,0	8,0	106,0	129,0
VAD 1	≈57,0	NP	?	121,0	0,0	91,0	24,0	7,0	6,5*	6,5*	15,0	14,0	0,0	8,0	33,0?	47,0?
Velstove Z1	?	?	?	158,0	0,0	119,0?	38,0?	9,5*?		-10,0*-	20,0	14,0	9,0	0,0	79,0	93,0
Weyhausen Z1	?	?	?	45,0	0,0	45,0?	?	?	?	?	14,0	9,0	0,0	14,0	70,0	79,0
Wilsum Z2	93,0	NP	?	55,0	0,0	20,0	21,0	16,0	-11,0*-		11,0	18,0	0,0	4,0	101,0	119,0
Zwischenahner Meer Z1	98,0	NP	?	134,0	0,0	80,0	35,0	20,0	-13,0*-		13,0	23,0	12,0	7,0	117,0	140,0
GERMAN NORTH SEA																
Q-1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
R-1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
S-1	88,0	NP	?	92,0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	≈150,0
DANISH NORTH SEA																
A-2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
U-1	32,0?	NP	17,0?	59,0	11,0	16,0	32,0	10,0*	5,0*	5,0*	20,0	,cannot be subdivided,				155,0
ONSHORE DENMARK																
Arnum-1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Orslev-1	OS?	OS?	8,0	0,0	-	-	-	-	-	-	12,0	,cannot be subdivided,				97,0
Ringe-1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Rodby-1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Slagelse-1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Tonder-1	OS?	OS?	11,0	46,0	,,,,,cannot correlate,,,,						14,0	,cannot be subdivided,			112,0	

Well Name	SMM	RSM	LRMM	MRHM	*a*	*b*	*c*	*d*	*e*	*f*	MREM	IRMM	URHM	UREM	URMM	MRMM

Thickness of Members in metres, For Abbreviations see KEY at end of Table 2

APPENDIX A - TABLE 2

Well Name	Operator	Comments	Thickness MDM	MHM	MEM	MMM	DDF	Depth Top BSST	DDF	CODES
ONSHORE U.K.										
Axholm 1	Candecca	Starts in MEM	42,5	0,0	?	NP	+114,0	107	NP	
Bardney 1	B.P.		41,0	0,0	20,0	37,5	162,5	650	488	
Barton 1	Home		39,0	0,0	17,6	40,8	162,2	344	182	
Burton-on -Stather 1	B.P.		44,5	0,0	16,7	40,8	176,2	273	97	
Corringham 8	B.P.		40,0	0,0	18,0	39,0	159,5	353	195	a
Cropwell Bishop 1	B.P.		MF	0,0	20,5	40,0	125,0	185	58	a
Cropwell Butler 1	B.P.	Starts in MMM	MF	0,0	21,0	?	+113,0	94	NP	a
Glentworth 4	B.P.		38,0	0,0	19,0	38,0	160,0	376	215	a
Harlequin 1	D'Arcy	Starts in MMM	MF	0,0	22,5	?	+103,0	60	NP	a
Hornsea 1	Texaco		49,0	0,0	18,9	47,5	202,7	859	657	
Hunmanby 1	Burmah		43,0	0,0	16,8	41,5	202,7	867	664	
Hunstanton 1	Place	Unconf MMM/RH	38,7	0,0	20,7	+19,8	+122,5	640	NP	A
Langar 1	B.P.		29,0	0,0	19,5	42,0	130,5	197	66	a
Locton 7	Home		40,5	0,0	14,3	41,1	209,1	843	634	
Nettleton 1	B.P.		39,5	0,0	17,6	39,6	162,7	728	565	
Nocton 7	D'Arcy		41,5	0,0	22,5	36,5	168,5	498	331	a
North Dalton 1	Candecca		45,0	0,0	15,2	43,0	183,5	397	208	
Plungar 12	D'Arcy		28,0	0,0	20,5	40,0	135,0	269	130	a
Redmile 1	B.P.		28,0	0,0	20,0	40,0	143,5	297	153	a
Ruskington 1	D'Arcy		42,0	0,0	18,5	39,0	156,0	588	430	a
Saxthorpe 1	Duntex	Unconf MMM/RH	41,8	0,0	19,8	+10,7	+104,9	650	NP	
Sibsey 1	Ball & Collins		40,5	.....very poor log.....				725	?	
Somerton 1	Conoco		29,9	0,0	17,0	41,4	105,8	730	625	
South Cliffe 1	Candecca		46,5	0,0	19,2	42,7	185,3	251	76	A
South Creake 1	B.P.	Unconf MMM/RH	44,5	0,0	18,9	+24,4	+128,0	623	NP	
STAITHES S20	Cleaveland Potash		36,6	0,0	14,3	36,9	154,2	550	397	E
Tetney Lock 1	B.P.		42,0	0,0	17,1	40,2	170,7	1113	942	a
Torksey 4	B.P.		41,0	0,0	21,0	36,2	159,4	275	115	
Welton 1	B.P.		40,0	0,0	13,0	42,0	162,5	564	402	
U.K. NORTH SEA										
36/23-1	Home	Unconf LB?/LC	U	U	U	U	U	NP	NP	
36/26-1	Placid	Unconf LB/LC	U	U	U	U	U	NP	NP	
37/23-1	Texaco	Unconf LB/LC	U	U	U	U	U	NP	NP	
38/16-1	Amoco	Unconf Zech/LC	U	U	U	U	U	NP	NP	
38/18-1	Arpet	Unconf LB/UJ	U	U	U	U	U	NP	NP	
38/22-1	Amoseas	Unconf LB/UJ	U	U	U	U	U	NP	NP	
38/25-1	Burmah	Unconf Zech/LC	U	U	U	U	U	NP	NP	
Well Name	Operator	Comments	MDM	MHM	MEM	MMM	DDF	BSST	DDF	CODES

For Codes and Abbreviations see KEY at end of Table 2.

APPENDIX A - TABLE 2 (continued)

Well Name	Operator	Comments	Thickness MDM	MHM	MEM	MMM	DDF	Depth Top BSST	DDF	CODES
38/29-1	Amoseas	Unconf LB/LC	U	U	U	U	U	NP	NP	
41/ 8-1	Home		35,4	0,0	14,0	38,0	153,6	287	133	
41/20-1	Signal		49,4	15,0	12,5	41,0	258,8	398	139	
41/24-1	Total		43,0	0,0	16,0	40,0	194,2	516	322	
42/13-1	B,P,	Diapir Zech/MDM	+30,2	0,0	15,5	38,1	+83,8	NP	1119	
42/14-1	Phillips		48,0	0,0	18,5	41,0	225,6	836	610	
42/23-1	Burmah		56,0	32,5	17,0	39,6	298,4	1218	920	
42/26-1	Texas Gas	Fault MRMM/UT	F	F	F	F	+67,7	1462	NP	
42/28-1	Amoco	Zech Diapir-No DDF	D	D	D	D	D	NP	NP	
42/28-2	Amoco	Fault in MDM	+46,0	0,0	18,6	40,8	+232,0	1859	1627	
42/29-1	B,P,		54,0	18,0	16,4	42,7	290,4	1689	1399	
42/30-1	B,P,		58,0	65,0	12,0	44,0	373,0	1685	1283	
43/ 3-1	Rycade		54,3	0,0	13,7	35,9	238,0	1697	1459	
43/ 7-1	Arpet		48,0	0,0	15,0	37,5	178,6	1531	1343	
43/ 8-1	Hamilton		64,0	0,0	16,2	41,8	294,4	1728	1416	
43/ 8-2	Hamilton		61,0	0,0	19,0	40,0	291,7	1860	1556	
43/11-1	Zapex		49,0	0,0	14,9	41,5	207,0	826	612	
43/16-1	Conoco		59,0	22,5	16,5	39,5	296,9	900	603	
43/17-1	Amoco		64,0	39,5	14,0	40,0	309,4	727	418	
43/20-1	Hamilton		72,5	41,0	13,7	46,9	383,1	1590	1192	
43/21-1	Mobil		61,0	36,0	12,2	39,5	323,7	1024	700	
43/30-1	Amoco		63,0	4,0	16,5	48,5	276,2	761	485	
44/ 2-1	Shell		62,0	44,5	15,2	42,4	282,0	2218	1912	
44/ 7-1	Amoco	Unconf URMM/LC	U	U	U	U	+50,3	1530?	NP	
44/14-1	Phillips	Unconf URMM/LC	U	U	U	U	+119,3	1667?	NP	
44/19-2	Burmah		70,5	0,0	19,0	47,0	323,7	1680?	1326	
44/21-1	Total		74,0	7,0	24,0	44,8	329,4	1512	1183	
44/23-1	B,P,		64,5	0,0	21,0	45,5	296,6	1340	1033	
44/24-1	B,P,		69,0	0,0	27,0	40,5	321,9	1849	1513	
44/26-1	Amoco		65,0	7,3	14,6	46,9	289,6	1237	948	
47/ 3-1	Amoco		57,0	62,5	12,2	46,0	336,4	2034	1697	
47/ 5-1	Phillips	Unconf MEM?/?	69,1	61,0	?	U	+339,5	891	NP	
47/ 8-1	Gulf		52,5	0,0	17,8	47,9	251,4	1466	1215	
47/ 8-2	Gulf		54,0	6,0	16,8	41,8	255,4	1544	1289	
47/ 9-1	Gulf/B,P,		55,5	73,0	12,8	50,0	381,0	1839	1458	
47/ 9-2	Gulf		53,0	0,0	18,9	43,9	246,9	1723	1476	
47/ 9-3	Gulf	Diapir Zech/MRHM	50,0	40,0	12,0	51,0	+294,0	NP	2002	
47/13-1	Conoco		47,0	0,0	15,8	38,4	210,9	1579	1368	
47/13-2	Conoco		48,0	0,0	16,5	47,0	212,8	1601	1389	
47/14-2	Burmah		47,5	0,0	18,5	43,0	205,4	1598	1392	
47/15-1	Phillips	Fault MEM/LJ	49,0	0,0	+2,0	F	+138,0	1642	NP	G
47/15-2	Amoco		49,0	0,0	18,6	39,6	199,3	1608	1409	
47/18-1	Burmah		42,5	0,0	15,5	45,0	182,9	1512	1330	
47/20-1	Burmah		44,5	0,0	16,8	45,4	192,9	1644	1450	
47/25-2	Placid		41,0	0,0	20,4	42,0	165,5	1298	1132	
47/29-1	Burmah		42,0	0,0	22,9	39,9	162,2	1019	857	
Well Name	Operator	Comments	MDM	MHM	MEM	MMM	DDF	BSST	DDF	CODES

For Codes and Abbreviations see KEY at end of Table 2.

Well Name	Operator	Comments	Thickness MDM	MHM	MEM	MMM	DDF	Depth Top BSST	DDF	CODES
48/ 3-1	Shell	Zech Diapir-No DDF	D	D	D	D	D	NP	NP	
48/ 6-2	B.P.		62.0	53.5	10.5	56.5	346.9	1330	983	
48/ 6-5	B.P.		60.0	66.0	7.5	64.0	369.4	1888	1519	
48/ 6-10	B.P.		61.0	69.0	11.5	55.0	368.5	1911	1543	
48/ 7-1	Amoseas		60.0	51.5	14.5	55.0	332.8	1109	773	
48/ 7-4	B.P.		60.0	61.0	13.0	45.0	355.0	2322	1967	
48/10-1	Phillips	Zech Diapir-No DDF	D	D	D	D	D	NP	NP	
48/11-1	Arpet	Fault URMM/MDM	+39.6	0.0	23.2	45.1	+188.0	1947	1711	J
48/11-2	Arpet		50.0	17.0	14.0	42.5	221.0	1690	1469	
48/12-1	Conoco		61.5	56.5	14.3	57.3	350.8	1457	1106	K
48/12-2	Transocean		54.9	50.3	12.5	54.6	317.0	1601	1284	
48/13-1	Shell		60.0	52.5	13.4	53.0	319.2	910	588	
48/13-2	Shell		62.0	42.5	13.1	47.5	304.4	1104	799	
48/17-1	Mobil		45.5	37.0	12.5	48.0	228.3	1455	1227	
48/18-2	Ranger		45.0	38.0	12.0	51.0	242.3	1734	1491	
48/19-1	Shell		55.5	54.0	8.5	52.0	312.1	1203	891	
48/20-1	Shell		55.8	59.0	9.0	54.0	327.4	1468	1141	
48/21-2	Placid		43.0	0.0	16.5	45.1	177.1	1524	1347	
48/22-2	Burmah		43.0	38.5	13.0	47.5	215.2	1412	1198	
48/25-1	Shell		59.5	60.5	11.0	55.0	304.2	1110	806	
48/28-1	Arpet		40.5	0.0	19.5	42.4	158.4	998	839	
48/29-5	Arpet	Unconf MEM/RH	47.2	0.0	+4.0	U	+108.5	1099	NP	
48/30-2	Phillips		48.0	30.5	13.5	51.0	210.3	995	785	
49/ 1-1	B.P.	Zech Diapir-No DDF	D	D	D	D	D	NP	NP	
49/ 2-1	Mobil	Unconf URHM/?UC	U	U	U	U	+43.3	423	NP	
49/ 2-2	Mobil	Unconf MB/UC	U	U	U	U	U	NP	NP	
49/ 5-1	Gulf	Unconf LB/LC	U	U	U	U	U	NP	NP	
49/ 6-2	Phillips		61.5	66.5	12.2	51.8	323.1	1469	1146	
49/ 6-3	Phillips		64.5	66.0	17.3	47.9	308.4	2805	2496	
49/ 8-1	Signal	Unconf LRMM/UC	U	U	U	U	+30.4	836	NP	
49/ 9-1	Shell	Unconf LB/LC	U	U	U	U	U	NP	NP	
49/10-1	Shell	Unconf LB/LC	U	U	U	U	U	NP	NP	
49/11-1	Phillips		59.4	54.3	13.7	47.2	333.1	1671	1338	
49/12-1	Conoco/NCB		65.0	66.0	14.9	47.9	329.8	1490	1189	
49/13-2	Gulf		66.0	0.0	21.6	44.2	230.7	1878	1647	
49/13-3	Conoco	Unconf MB/LC	U	U	U	U	U	NP	NP	
49/13-4	Conoco	Unconf MB/UC	U	U	U	U	U	NP	NP	
49/14-1	Amoseas	Unconf LB/LC	U	U	U	U	U	NP	NP	
49/16-1	Conoco		61.0	54.9	16.2	55.2	339.5	1400	1060	
49/17-1	Conoco		63.0	58.0	9.7	56.7	312.0	1360	1048	
49/18-2	Amoco		65.0	0.0	14.0	57.3	248.0	1444	1175	
49/19-1	Shell	Unconf LB/LC	U	U	U	U	U	NP	NP	
49/19-3	Shell		63.0	0.0	17.4	48.8	211.0	1466	1255	H
49/20-1	Total	Unconf LB/LC	U	U	U	U	U	NP	NP	
49/20-2	Shell	Unconf LB/LC	U	U	U	U	U	NP	NP	
49/21-2	Conoco	Fault MDM & MMM	+8.0	+40.0	9.1	+39.6	+214.0	1344	1130	C
49/21-3	Conoco		64.0	67.0	12.5	57.0	329.4	1295	965	
49/22-2	Conoco		62.0	65.0	6.1	58.8	319.0	1749	1430	
49/22-3	Conoco		61.0	50.0	10.1	52.2	293.0	1414	1120	
49/23-2	Amoco		61.0	62.0	11.0	53.5	294.0	1528	1235	
Well Name	Operator	Comments	MDM	MHM	MEM	MMM	DDF	BSST	DDF	CODES

For Codes and Abbreviations see KEY at end of Table 2.

APPENDIX A - TABLE 2 (continued)

Well Name	Operator	Comments	Thickness MDM	MHM	MEM	MMM	DDF	Depth Top, BSST	DDF	CODES
49/23-4	Amoco	Diapir Zech/URMM	60,4	73,0	11,2	56,1	+221,0	NP	1874	
49/24-1	Shell	Unconf MB/LC	U	U	U	U	U	NP	NP	
49/24-2	Shell	Unconf LB/LC	U	U	U	U	U	NP	NP	
49/24-3	Shell	Unconf MB/LC	U	U	U	U	U	NP	NP	
49/24-4	Shell	Unconf MB/LC	U	U	U	U	U	NP	NP	
49/24-12	Shell	Unconf MB/LC	U	U	U	U	U	NP	NP	
49/24-16	Shell	Unconf MMM/LC	65,5	0,0	14,0	+34,0	+207,0	1446	NP	
49/25-1	Allied/Shell	Unconf LB/UC	U	U	U	U	U	NP	NP	
49/25-2	Shell	Unconf LB/LC	U	U	U	U	U	NP	NP	
49/25-3	Shell	Unconf MRHM/?	U	U	U	U	+15,5	1596	NP	
49/26-4	Shell		53,4	58,0	10,7	58,8	287,0	869	583	
49/27-3	Amoco		60,0	54,0	10,9	57,0	279,8	928	648	
49/28-3	Arpet		61,0	66,0	11,0	52,0	307,5	1447	1139	
49/29-1	Shell	Unconf MDM/?	+53,0	U	U	U	+130,2	1589	NP	
49/30-1	Amoco	Unconf MB/LC	U	U	U	U	U	NP	NP	
49/30-2	Amoco	Unconf MB/LC	U	U	U	U	U	NP	NP	
49/30-3	Amoco	Unconf MB/LC	U	U	U	U	U	NP	NP	
50/26-1	Amoseas	Unconf MDM/LC	+46,6	U	U	U	+128,0	1765	NP	
52/ 5-2	Phillips		43,0	0,0	16,2	49,0	152,1	852	700	
52/ 5-11	Phillips		40,5	0,0	16,5	40,2	114,3	1061	946	
53/ 1-1	Mobil		46,0	25,0	15,2	52,1	205,4	982	776	
53/ 1-2	Mobil		45,5	0,0	24,5	47,0	159,7	931	771	
53/ 1-3	Mobil	Fault - No DDF	F	F	F	F	F	NP	NP	
53/ 2-3	Mobil		59,0	40,0	12,8	56,3	253,6	1050	798	
53/ 3-1	Gulf	Fault BSST/MRMM	66,0	0,0	22,0	46,0	+142,0	NP	1160	
53/ 4-1	Signal	Unconf LB/LC	U	U	U	U	U	NP	NP	
53/ 4-2	Signal	Unconf LB/LC	U	U	U	U	U	NP	NP	
53/ 4-3	Signal	Unconf MDM/UC	+38,5	U	U	U	+116,4	1521	NP	
53/ 4-4	Signal	Unconf MMM/LC	61,5	0,0	21,5	+48,5	+206,3	1210	≈1004	H
53/ 5-1	Amoco	Unconf Zech/LC	U	U	U	U	U	NP	NP	
53/ 7-1	Arpet		50,5	0,0	27,4	48,7	173,4	940	766	
53/ 7-2	Arpet		50,5	0,0	27,5	52,0	178,9	879	701	
53/ 8-1	Gulf		51,0	0,0	14,9	47,9	165,2	884	719	
53/10-1	Gulf	Unconf LB/LC	U	U	U	U	U	NP	NP	
53/12-1	Arpet		38,0	0,0	20,5	58,0	143,3	994	851	
53/12-3	Arpet		35,6	0,0	23,0	54,0	122,8	785	664	
53/14-1	Shell	Unconf MB/LC	U	U	U	U	U	NP	NP	
53/16-1	Arpet	Unconf MB/LC	U	U	U	U	U	NP	NP	
53/19-1	Arpet	Unconf MMM/LC	34,0	0,0	23,0	+40,0	+112,8	893	NP	
54/ 1-1	Conoco/NCB	Unconf MB/LC	U	U	U	U	U	NP	NP	
54/11-1	Amoco	Unconf LB?/LC	U	U	U	U	U	NP	NP	
DUTCH NORTH SEA										
B/17-2	Tenneco	Unconf MMM/?	101,1	0,0	12,0	+37,0	+436,0	3193?	NP	
D/15-1	Phillips	Unconf MB/LC	U	U	U	U	U	NP	NP	
Well Name	Operator	Comments	MDM	MHM	MEM	MMM	DDF	BSST	DDF	CODES

For Codes and Abbreviations see KEY at end of Table 2.

APPENDIX A - TABLE 2 (continued)

Well Name	Operator	Comments	Thickness MDM	MHM	MEM	MMM	DDF	Depth Top BSST	DDF	CODES
E/16-1	Placid	Unconf LB/LC	U	U	U	U	U	NP	NP	
E/17-1	Union	Unconf LB/LC	U	U	U	U	U	NP	NP	
F/ 4-1	Union		63,0	0,0	16,0	49,0	286,0	2356?	2070	H
F/ 7-1	Conoco	Unconf SMM/LC	U	U	U	U	+16,0	1789?	NP	
F/ 9-1	Conoco	Zech Diapir-No DDF	D	D	D	D	D	NP	NP	
F/10-1	Petroland		73,0	0,0	19,0	52,0	253,0	2546?	2292	
F/14-2	Placid	Zech Diapir-No DDF	D	D	D	D	D	NP	NP	
F/15-1	NR	Unconf URMM/LC	U	U	U	U	+153,0	NR	NP	
G/17-1	Arco	Unconf ?/?-No DDF	U	U	U	U	U	NP	NP	
K/ 6-1	Petroland	Unconf LB/LC	U	U	U	U	U	NP	NP	
K/ 7-1	NAM	Unconf LB/LC	U	U	U	U	U	NP	NP	
K/ 7-2	NAM	Unconf MB/LC	U	U	U	U	U	NP	NP	
K/ 8-1	NAM	Unconf LB/LC	U	U	U	U	U	NP	NP	
K/ 9-1	Placid	Unconf MB/LC	U	U	U	U	U	NP	NP	
K/11-1	Placid	Unconf MB/LC	U	U	U	U	U	NP	NP	
K/11-2	Placid	Unconf MB/LC	U	U	U	U	U	NP	NP	
K/12-1	Arco		82,0	0,0	18,0	45,0	311,0	2343	2018	
K/13-1	Pennzoil		64,0	0,0	12,5	59,0	221,0	1375	1152	
K/14-1	NAM		72,0	43,0	17,0	42,0	304,0	2088	1780	
K/17-1	NAM		74,0	41,5	21,0	48,0	330,0	1748	1404	
K/17-2	NAM	Diapir Zech/MRHM	68,0	44,0	12,0	49,0	+241,0	NP	1547	
L/ 2-1	NAM		83,0	114,0	19,0	55,0	597,0	3939	3324	
L/ 2-2	NAM	Unconf MEM?/RH	84,0?	0,0	+10,0?	U	+551,0	3604	NP	
L/ 7-1	Petroland	Unconf MDM/LC	+65,0	U	U	U	+191,0	2531	NP	
L/ 8-1	Pennzoil	Unconf LB/UJ	U	U	U	U	U	NP	NP	
L/10-1	Placid	Unconf MEM/LC	71,0	0,0	+15,0	U	+265,0	3195	NP	
L/10-2	Placid	Unconf Zech/LC	U	U	U	U	U	NP	NP	
L/10-3	Placid	Unconf LB/LC	U	U	U	U	U	NP	NP	
L/10-4	Placid	Unconf LB?/LC	U	U	U	U	U	NP	NP	
L/10-7	Placid	Unconf LB/LC	U	U	U	U	U	NP	NP	
L/11-1	Placid	Unconf LB/LC	U	U	U	U	U	NP	NP	
L/12-1	Signal	Zech Diapir-No DDF	D	D	D	D	D	NP	NP	
L/13-1	NAM	Unconf LB?/LC	U	U	U	U	U	NP	NP	
M/ 7-1	Phillips	Unconf Zech/LC	U	U	U	U	U	NP	NP	
M/ 9-1	NAM	Unconf LB/LC	U	U	U	U	U	NP	NP	
N/ 4-1	Pennzoil	Unconf ?/?-No DDF	U	U	U	U	U	NP	NP	
P/ 2-1	Tenneco		73,0	51,0	17,0	52,0	258,0	2422	2088	
P/ 5-1	Petroland	Unconf LB/LC	U	U	U	U	U	NP	NP	
P/ 6-1	Mobil		69,0	37,0	?	?	276,0?	2619	?	
P/ 6-2	Mobil		69,0	43,0	22,0	49,0	288,0	2231	1910	
P/ 7-1	Union	Unconf LB/LC	U	U	U	U	U	NP	NP	
P/ 9-1	Amoco		57,0	12,5	15,0	51,0	225,0	3848	3623	
P/10-1	Pennzoil	Unconf LB/LC	U	U	U	U	U	NP	NP	
P/12-1	Phillips		53,0	0,0	23,0	45,0	198,0	3040?	2842	

Well Name | Operator | Comments | MDM | MHM | MEM | MMM | DDF | BSST | DDF | CODES

For Codes and Abbreviations see KEY at end of Table 2.

Well Name	Operator	Comments	Thickness MDM	MHM	MEM	MMM	DDF	Depth Top BSST	DDF	CODES
Q/ 1-1	Union		64,0	0,0	21,0	45,0	200,0	2048	1848	
Q/ 4-1	B.P./Gulf		64,6	46,0	17,0	55,5	303,0	2255	1952	
Q/ 8-1	NR	Unconf MMM/LJ	71,0	0,0	11,0	+52,0	+256,0	NR	NP	
Q/10-2	NAM	Unconf MEM/LC	75,0	0,0	+2,0	U	+174,0	1787?	NP	
Q/11-1	NAM	Unconf MMM/LJ	...contacts unclear...				+168,0	2335?	NP	
ONSHORE NETHERLANDS										
Amsterdam (east)	NR		93,0	60,0	21,0	54,0	388,0	NR	NR	
Blijham-1	NAM		114,0	62,5	19,0	58,0	583,0	2732	2143	A b
Eleveld-101	NAM	Unconf MMM/?	103,0	0,0	26,0	+48,0	+449,0	2513	NP	A b
Emmen-7	NAM		122,0	27,5	24,0	61,0	588,0	2328	1717	A b
Gelderland	NR		92,0	0,0	25,0	58,0	334,0	NR	NR	
Hengelo-31	KNZ	Starts in MDM	+44,0	NP	NP	NP	+317,0	ND	NP	I k
Noord Holland 1	NR	Unconf LB/LC	U	U	U	U	U	NP	NP	
Noord Holland 2	NR	Unconf MMM/LC	67,0	0,0	17,0	+50,0	+270,0	NR	NP	
Noord Holland 3	NR		64,0	17,5	16,5	58,0	262,0	NR	NR	
Sleen-4	NAM		121,0	12,0	36,0	57,0	502,0	1889	1361	A b
Krabbendam	ND	Unconf LB/LC	U	U	U	U	U	NP	NP	f
Vijk 5	ND	Unconf MDM/LC	+90,0	U	U	U	ND	ND	ND	c
Vijk 7	ND	Unconf LB/LC	U	U	U	U	U	NP	NP	c
Vijk 13	ND	Unconf SMM/LC	U	U	U	U	U	ND	ND	c
Vijk 21	ND	Unconf MRMM/LC	U	U	U	U	+229,0	ND	ND	c
Zuid Holland	NR		82,0	0,0	21,0	59,0	272,0	NR	NR	
ONSHORE GERMANY										
Bielefeld 1	ND		ND	ND	ND	ND	ND	ND	ND	i
Bockenem 1	ND		ND	ND	ND	ND	ND	ND	ND	i
Eldingen	ND		ND	ND	ND	ND	ND	ND	ND	j
Emlichheim Z1	ND		ND	ND	ND	ND	ND	ND	ND	d
Emsland	NR		126,0	67,0	22,0	62,0	622,0	NR	NR	
Ems River Mouth	NR		104,0	49,0	19,0	52,0	497,0	NR	NR	
Getelo Z1	ND		ND	ND	ND	ND	ND	ND	ND	d
Harpstedt Z1	ND		ND	ND	ND	ND	ND	ND	ND	d
Kassebruch T2	ND		ND	ND	ND	ND	ND	ND	ND	d
Lieme 1	ND		ND	ND	ND	ND	ND	ND	ND	i
Messingen Z1	ND		ND	ND	ND	ND	ND	ND	ND	i
Nord deutschland 5	ND		ND	ND	ND	ND	ND	ND	ND	i
Ratzel T1	ND		ND	ND	ND	ND	ND	ND	ND	d
Rehden 8	ND		ND	ND	ND	ND	ND	ND	ND	i
South Bremen	NR		123,0	90,0	20,0	59,0	642,0	NR	NR	
South Hannover	NR		118,0	0,0	20,0	81,0	584,0	NR	NR	
VAD 1	ND	Fault MDM & MMM?	86,0?	53,0	26,0	38,0?	452,0	809	252	l

Well Name | Operator | Comments | MDM | MHM | MEM | MMM | DDF | BSST | DDF | CODES

APPENDIX A - TABLE 2 (continued)

Well Name	Operator	Comments	.....Thickness..... MDM	MHM	MEM	MMM	DDF	Depth Top, BSST	DDF	CODES
Velstove Z1	ND		ND	ND	ND	ND	ND	ND	ND	j
Veyhausen Z1	ND		ND	ND	ND	ND	ND	ND	ND	j
Wilsum Z2	ND		ND	ND	ND	ND	ND	ND	ND	d
Zwischenahner Meer Z1	ND		ND	ND	ND	ND	ND	ND	ND	d
GERMAN NORTH SEA										
Q-1	ND	Unconf Zech/LC	U	U	U	U	U	NP	NP	h
R-1	Transocean	Ends in MHM	ND	+61,0	ND	34,0	ND	ND	2941	h
S-1	Transocean		85,0	75,0	...39,0...		529,0	2055	1547	h
DANISH NORTH SEA										
A-2	ND		ND	ND	ND	ND	+333,0	ND	ND	g'
U-1	ND		≈119,0	87,0	20,0	?	?	ND	ND	e
ONSHORE DENMARK										
Arnum-1	ND		ND	ND	ND	ND	≈274,0	ND	1103	g'
Orslev-1	ND		...cannot correlate...				≈246,0	1072	818?	g
Ringe-1	ND		ND	ND	ND	ND	≈202,0	ND	861	g'
Rodby-1	ND		ND	ND	ND	ND	≈343,0	ND	782	g'
Slagelse-1	ND		ND	ND	ND	ND	≈234,0	ND	1590	g'
Tonder-1	ND		...cannot correlate...				≈352,0	1610	1255?	g

Well Name	Operator	Comments	MDM	MHM	MEM	MMM	DDF	BSST	DDF	CODES

Appendix A - Key to Tables

All thicknesses are in metres. Depths are in metres below sea level unless stated.

STRATIGRAPHY

UC	Upper Cretaceous
LC	Lower Cretaceous
UJ	Upper Jurassic
LJ	Lower Jurassic
RH	Rhaetic
UT	Upper Triassic ('Keuper')
DDF	Dowsing Dolomitic Formation
MMM	Muschelkalk Mudstone Member
MEM	Muschelkalk Evaporite Member
MHM	Muschelkalk Halite Member
MDM	Muschelkalk Dolomitic Member
MRMM	Main Röt Mudstone Member
URMM	Upper Röt Mudstone Member
UREM	Upper Röt Evaporite Member
URHM	Upper Röt Halite Member
IRMM	Intermediate Röt Mudstone Member
MREM	Main Röt Evaporite Member
MRHM	Main Röt Halite Member
LRMM	Lower Röt Mudstone Member
RSM	Riff Sandstone Member
SMM	Solling Mudstone Member
BSST	Bunter Sandstone Formation
MB	Middle Bunter
LB	Lower Bunter
Zech	Zechstein

GENERAL

D	Absent due to Zechstein diapirism
•	Cycle non-halitic, recognisable equivalent
F	Absent due to faulting
MF	Marginal facies
ND	No data
NP	Not present
NR	Non-released well - data not available
OS	Absent due to overstep
Unconf	Unconformity
U	Absent due to erosion at unconformity
?	Contact/Member unclear

CODES

A	Depths below K.B., not sea level
C	Triassic type-well (Rhys 1974)
E	Cored Middle Triassic intersection studied
G	Correlation of well uncertain
H	Top DDF close to unconformity
I	Well ends in SMM
J	Reverse fault in MRHM
K	Proposed DDF type-well 48/12-1

Noord Holland - Well name in *Italics*, Well not released, name changed (on land), no absolute depths quoted and location only approximate.

DATA FROM REFERNCES

a	Gamma-ray log from Balchin and Ridd (1970)
b	part of Gamma-ray and Sonic logs presented in NAM/RGD (1980). Full logs provided by NAM
c	Gamma-ray log from Gdula (1983)
d	Gamma-ray log for Solling Folge and Röt from Trusheim (1971)
e	Gamma-ray and Sonic log from Michelsen and Andersen (1983)
f	data (no logs) from van Lith (1983)
g	Gamma-ray and Sonic logs from Bertelsen (1980)
g'	data (no logs) from Bertelsen (1980)
h	data (no logs) from Best *et al*, (1983)
i	Gamma-ray log from Boigk (1959)
j	Gamma-ray log for Solling Folge and Röt from Philipp (1960)
k	data (no logs) from Visscher (1966)
l	Gamma-ray and Sonic logs from Kelch and Paulus (1980)

APPENDIX B

SURFACE GAMMA-RAY PROFILE (KIRTON BRICKWORKS, NOTTINGHAMSHIRE)

DETAILS OF METHOD AND DATA VALIDITY

As noted in Chapter 4, nowhere in the literature is the method for obtaining an outcrop gamma-ray profile adequately described. Provo *et al.* (1978) and Potter *et al.* (1980) only note that readings are taken every 0.8 metres and 0.2 metres respectively, and only a brief discussion of the instrument and method appears in Lucas (1971).

Due to this lack of published information the details of, and reasons for the method used are considered below.

B.1 INSTRUMENT

The instrument used was a portable, battery operated, 'Nuclear Enterprises 1700' Scintillometer with a 8 cm Sodium Iodide (NaI) crystal. Attached to the Scintillometer was a count-meter. Total gamma-ray count only was recorded.

B.2 ERRORS

In devising a method, an attempt was made to reduce as much as possible errors during measurement. These errors arise from (a) the statistical nature of gamma radiation, (b) the presence of background radiation, both cosmic and terrestrial and (c) variations in the sensitivity of the instrument itself.

(a) The statistical error has a 'Normal' distribution (Duivenstijn and Venverloo 1963, p.98), and the Standard Deviation (σ) is defined as

$$\sigma = \sqrt{N} \qquad (1)$$

where N is the total number of counts. Expressed as a percentage, the relative error (ϵ) is

$$\epsilon = 1/\sqrt{N} \qquad (2)$$

It was found from observation that, in the range of gamma-ray values measured from the Kirton succession, using the above instrument, a one minute count period gave a Relative Error of 2% - 3% (for gamma-ray values of 2,200 - 1,200 counts per minute (cpm) respectively) and the 2σ (96% confidence) error bar was hence less than 100 cpm. A one minute count period was therefore considered sufficient to keep statistical error low.

(b) Although the instrument was most sensitive to gamma radiation at the face of the scintillation crystal, it was also quite sensitive along the sides. This meant that the total gamma-ray count was due not only to radiation from the point of measurement, but was an average from the area immeadiately surrounding. This is not however considered a problem as a similar averaging over an interval occurs in down-the-hole surveys where a typical logging speed of 1800 feet/hour and a time constant of 2 seconds (Schlumberger 1972a, p.58) gives a gamma-ray value averaged over about 30 cm. The main effect of the unshielded sides of the crystal was

that the background gamma-ray value (1,100 - 1,200 cpm) represented a large percentage of the total signal.

Due to the high energy of the gamma-rays (about 1MeV), a 1/8th inch lead sleeve made to fit around the sides of the crystal had little effect on the number of gamma-rays reaching the instrument and hence was disguarded. An effective shield would have made the instrument too heavy for practical field use.

(c) The sensitivity of the instrument itself may be affected by temperature changes and battery drain. The instrument contains, as well as the scintillator crystal, a photomultiplier tube whose sensitivity is temperature dependant. It was thought too that, although the batteries were new, their efficiency might vary each time the instrument was switched on and during use. It was not possible to reduce these sources of error but, in order to gain some knowledge of their effects, a gamma-ray Standard was frequently measured.

The Standard was a Radium source (a luminous clock hand) mounted in a plastic sleeve which fitted over the face of the scintillator crystal in such a way that the source was always in the same position relative to the crystal. Allowing for statistical error, variations in the measured values of the Standard reflect variations in the sensitivity of the instrument.

B.3 DETAILS OF THE METHOD

Taking into account the need to minimise the errors mentioned above, the following method was used in the field:

The whole sequence was first logged lithologically. Then, starting from the base, the natural radioactivity was measured at 1/3rd metre intervals upto the highest accessable point. Although the exposure was continuous, in practice only about 5 metres of section was accessable at any one point. Each of these individual sections was treated separately.

The accessable section was marked out into 1/3rd metre intervals and the positions of measurement points coinciding with distinctive lithological horizons were marked on the lithological log. At each measurement point a clean flat surface was produced. The instrument was then switched on and left to 'settle down' for about 30 seconds to one minute. The Standard was measured at about 5 to 10 metres from the outcrop and then measurements were taken successively up the section, at the marked points, with the face of the crystal flat against the rockface. After every fifth reading and again at the end of the section, prior to switching the instrument off, the Standard was measured again. All measurements were for a period of one minute.

Further along the quarry the next accessable section was then marked out and the procedure repeated. In total 118 gamma-ray readings were taken up the section and the Standard was measured 47 times.

B.4 THE GAMMA-RAY PROFILE - DATA VALIDITY

The gamma-ray values measured in the field are presented in column 2 of fig. 4.4. Alongside in column 3 are the measured values of the Standard. In the discussion that follows terms such as 'high' and 'low' gamma-ray count refer only to the relative gamma-ray values within this profile.

As noted in section B.2.(b), the nature of the instrument results in a high background gamma-ray count. The error on the mean background of 1,150 cpm (2σ = 68 cpm), plotted on fig. 4.4 column 2, shows that almost all readings are sufficiently above background to be considered valid.

In order to determine whether the apparent variation in gamma-ray values measured up the section is 'real' or due to the statistical nature of the gamma radiation (see B.2.(a)), the 2σ error bars were calculated for each reading. As each reading comprises of signal + background, the 2σ error bars were calculated by the Law of Propagation of Errors (Duivenstijn and Venverloo 1963).

$$2\sigma = 2 \times \sqrt{\sigma_b^2 + \sigma_m^2} \qquad (3)$$

where σ_b and σ_m are the standard deviation of the background and the total signal respectively. In all cases 2σ varied between 97 - 117 cpm. The error bars are shown on fig. 4.4 column 2. While many small peaks fall within this range of statistical error and should hence be considered dubious, there are other peaks which cannot be explained solely in this way.

The error bars for the Standard were calculated in a similar manner (2σ = 134 - 174 cpm) but they are too small to show on fig. 4.4 column 3. Hence once again the variation in measured values was greater than the statistical variation. Hence there are 'real' variations in both the field data and the Standard up the section.

It was noted earlier (section B.2.(c)) that the Standard was measured to show variations in the sensitivity of the instrument and hence high (or low) field readings associated with similarly high (or

low) values of the Standard may be suspect. For example, particularly in the lower part of the profile, the higher gamma-ray counts do appear to coincide with the higher values of the Standard, suggesting that the peaks may in part be due to an increase in the counting efficiency of the instrument. The alternative explanation, that the Standard reads high because it was measured in the proximity of rocks with a high gamma-ray count, is considered unlikely because the high gamma-ray zones are relatively thin and the Standard was measured a few metres from the outcrop.

In order to determine which peaks should be considered suspect, a profile was produced, corrected for instrument drift (fig. 4.4 column 4). These corrections were based on two assumptions; (i) that between each measurement of the Standard the rate of drift of the Standard was constant and (ii) that between switching the instrument on and off, readings were taken at equal intervals. Hence a 'theoretical' value of the Standard could be calculated for each data point. The percentage difference between this 'theoretical' value and the mean value of the Standard (approximately 4,400 cpm) at each data point was calculated and the field data was then corrected by this percentage to produce the corrected profile in fig. 4.4 column 4.

Because of the assumptions made, the 'corrected' profile has not been considered as necessarily representing the true gamma-ray readings and has hence only been used to indicate those parts of the section where the original data may be suspect due to instrument drift.

Over the vast majority of the section the two profiles are very similar and all the major peaks on the field data profile, i.e. those outside the 2σ error limit, are (with only one exception) recognised on the 'corrected' profile. The exception, the peak at 6.4 metres, in the

upper part of Zone 1 (fig. 4.4), is hence considered suspect but not necessarily invalid.

As a further check on the data quality, a short overlapping section (at about 30 metres, in Zone 3) was logged in different parts of the quarry. Fig. 4.4 shows that there is a close similarity between the two profiles.

When statistical and instrument error have been considered, the general shape of the field gamma-ray profile remains the same, and hence the use of this profile for correlation purposes is considered valid. The close relationship between gamma-ray count and lithology, discussed in Chapter 4 (section 2.4) further confirms this validity.

APPENDIX C

THE FORMATION DENSITY LOG, AN APPARENT SALINITY INDICATOR

The following text and figures were presented as a poster display at the British Sedimentological Research Group annual meeting at Nottingham University, December 1986.

Of all the petrophysical logs, the Formation Density (FDC) log most clearly reflects salinity changes in evaporite basins. In the frequently uncored anhydrite - halite - K/Mg salt sequence, the trend to higher evaporite facies is matched by a trend to lower FDC log densities (fig. C.1), and hence major evaporite cycles (like those in the Permian Zechstein of the Southern North Sea area) are easily identified (fig. C.2). The prime value of the FDC log however, is that it is sensitive to detailed lithological variations (and hence salinity fluctuations) within individual cycles.

The FDC log in the Zechstein Z2 cycle evaporites (fig. C.2) records a gradual, rather than abrupt, transition from anhydrite to halite precipitation. The diagenetic alteration of much of the anhydrite to polyhalite (both of which have similar densities) little affects this overall log profile. A similar gradual transition between evaporite facies (albeit thinner) is also seen in the Z3 and Z4 cycles.

In each cycle, the onset of halite precipitation indicates an increase in the basin salinity. Further anhydrite precipitation requires the influx of new marine water into the basin. The gradual decrease in the amount of anhydrite through the cycle implies a reduction in this rate of influx, and a resulting salinity increase. In detail, the rate of influx can vary abruptly. The FDC log in fig. C.3 (a detail of fig. C.2)

records the rapid lithology variations resulting from minor salinity changes superimposed on a major evaporite cycle.

The FDC log shows that salinity fluctuations within the thicker Zechstein cycles take the form of correlatable second and third-order cycles (fig. C.4). Each sub-cycle starts with an abrupt increase in density, followed by a gradual upward decrease. This is the result of a sudden reduction in salinity at the start of the cycle, followed by a gradual return to higher salinities. The asymmetrical nature of these second and third-order cycles tends to suggest eustatic fluctuations outside the Zechstein Basin (sudden sea-level rises followed by gradual sea-level falls), rather than rapid fluctuations in evaporation rates.

In fig. C.5, a normal Zechstein succession is compared with that in an area of halokinetic salt withdrawal. Sub-cycles within the halites, identified on the FDC log, provide markers constraining the zones of salt movement. Z2 anhydrites/polyhalites and the Z4 cycle are almost unaffected. Movement is restricted to the more mobile K/Mg salts, and to the halites immediately above and below the Z3 dolomite/anhydrite. This latter unit has been squeezed out in the area of salt withdrawal.