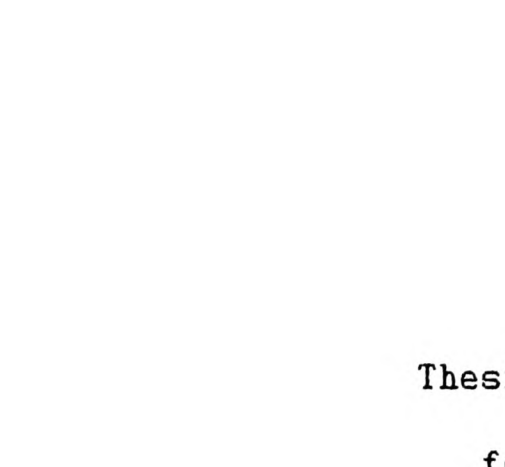
Thesis presented to the University of Oxford

for the Degree of Doctor of Philosophy

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

VOLUME 2: FIGURES, PLATES AND ENCLOSURES



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Enclosure Well E	U.K. Well 53/7-2
Enclosure Well F	U.K. Well 53/12-3
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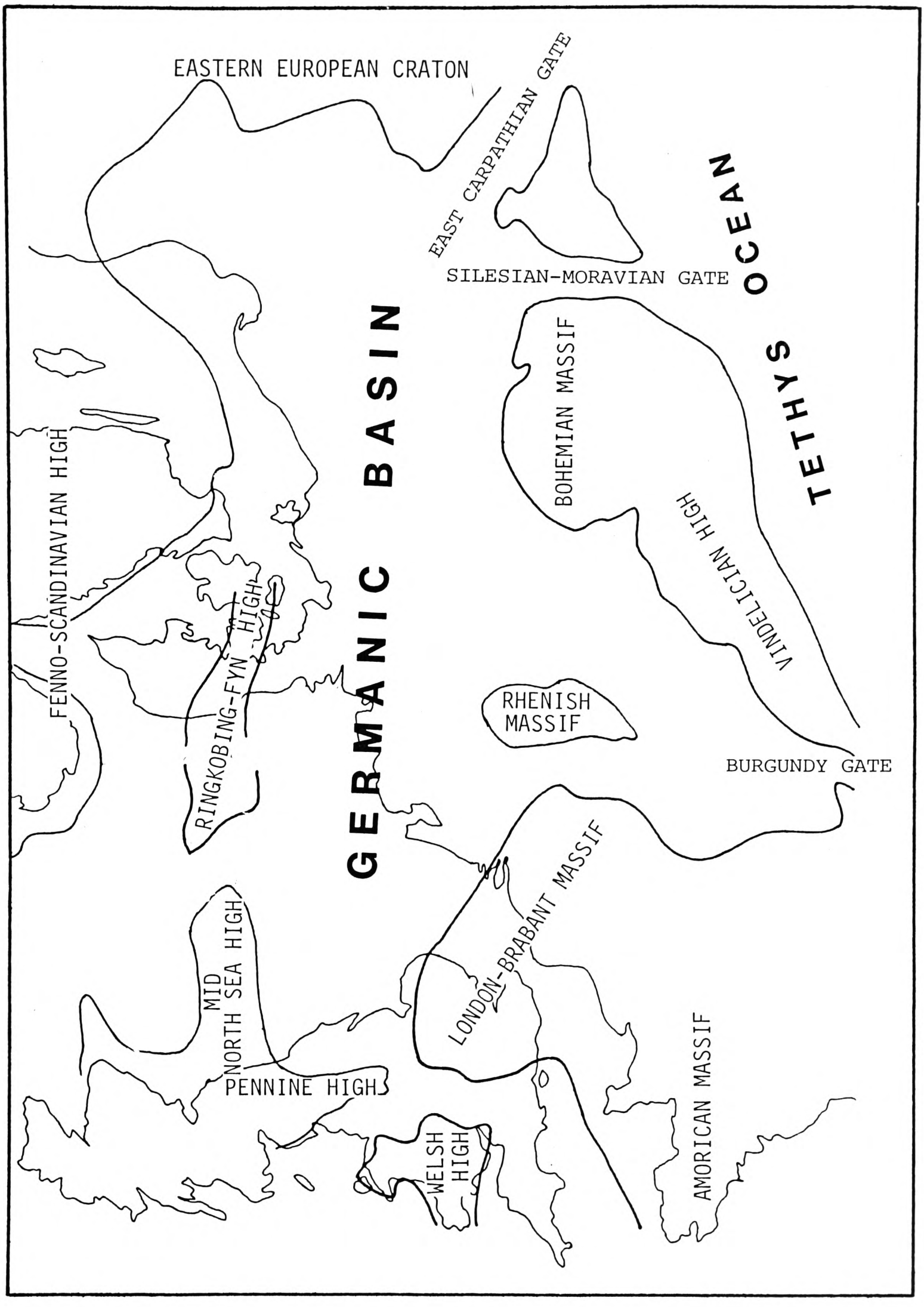


FIG. 1.1

THE GERMANIC BASIN AND ITS BOUNDING HIGHS

BF = Broad Fourteens Basin
BS = Northeast Brandenberg Swell
DF = Dowsing Fault Zone
ES = Eichsfeld Swell
ET = Ems Trough
HS = Hunte Swell
NN = North Netherland Swell
RS = Rugen Swell
TW = Thuringian Depression
WD = Weser Depression

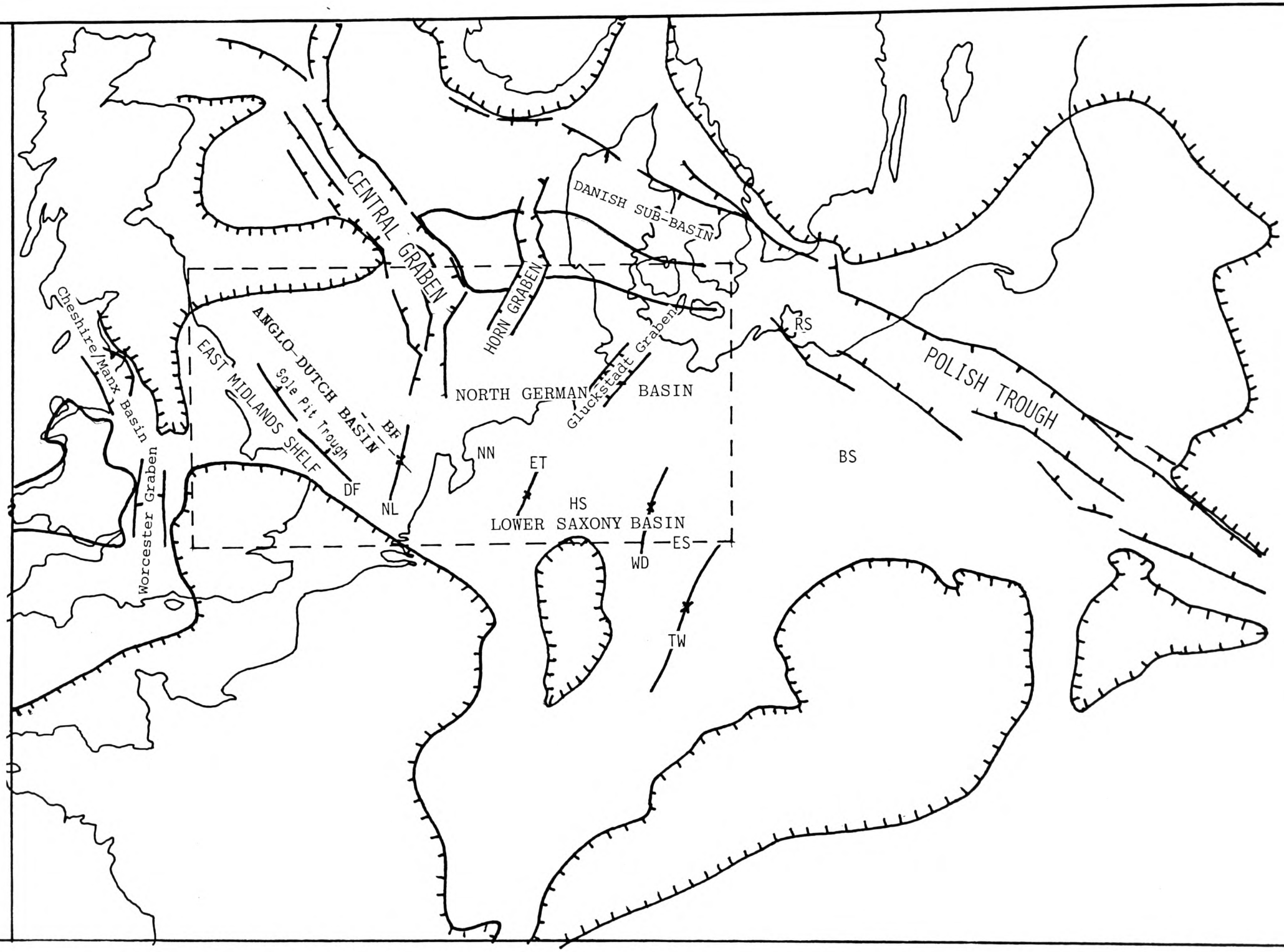


Fig. 1.2
Structural setting of the Germanic Basin, showing the study area.

(after Ziegler 1982a)

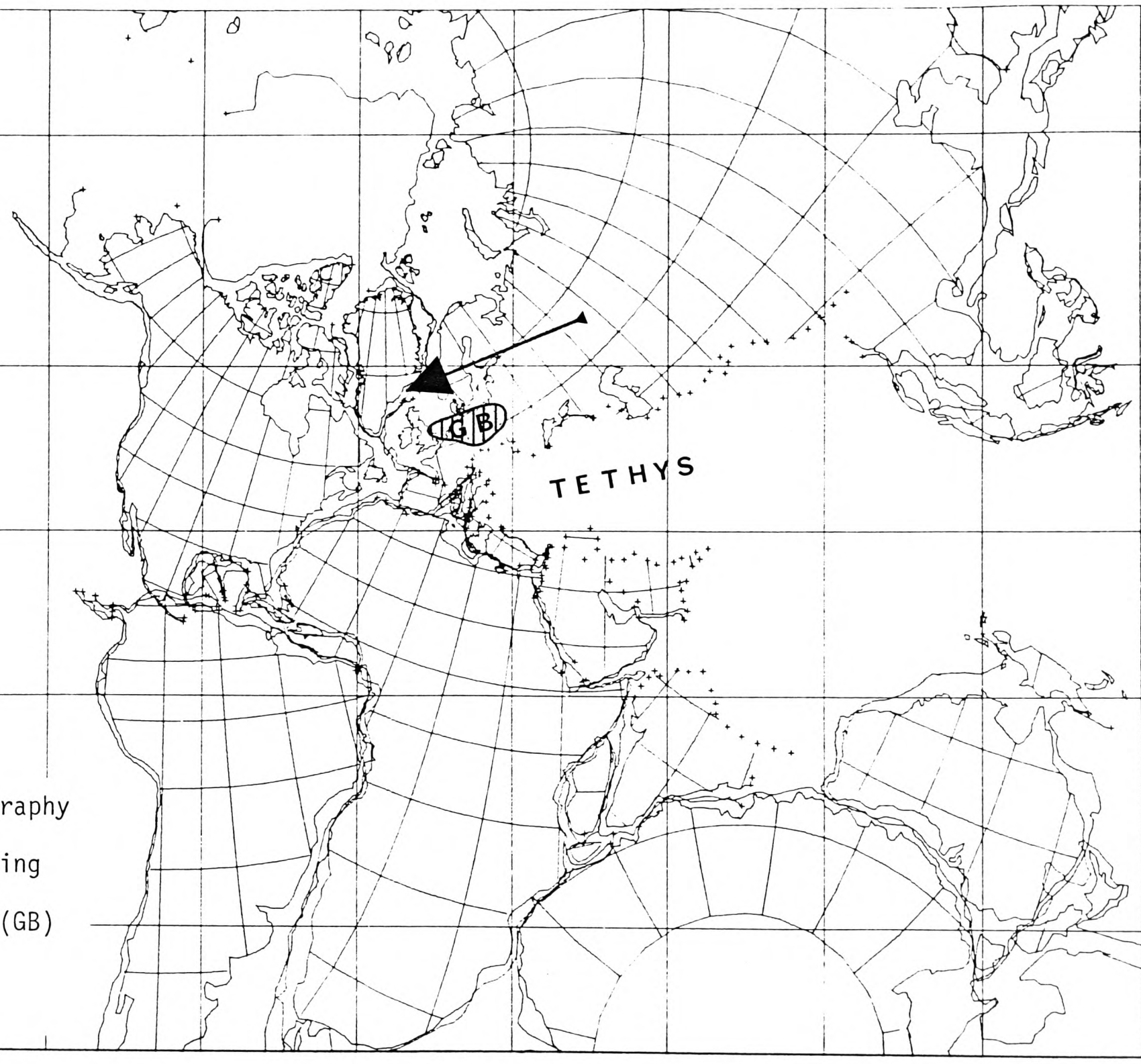


FIG. 1.3 Early Triassic Palaeogeography (after Smith and Briden 1977), showing the position of the Germanic Basin (GB) and the prevailing wind direction (Clemmensen 1979)

Fig. 1.3

Rheatic Transgressive Phase	Penarth Group	Winterton Formation				Upper	RHAETIAN
late Triassic Regressive Phase	Mercia Mudstone Group	HAISBOROUGH GROUP	Triton Anhydritic Formation	UPPER GERMANIC TRIAS	**Keuper Formation**	Keuper	NORIAN
			Dugeon Saliferous Formation				CARNIAN
						Lower	LADINIAN
MIDDLE TRIASSIC TRANSGRESSIVE PHASE			DOWSING DOLOMITIC FORMATION		**MUSCHELKALK FORMATION**	UPPER	
						MIDDLE MUSCHELKALK	ANISIAN
						LOWER	
					RöT FORMATION	UPPER	
early Triassic Regressive Phase	Sherwood Sandstone Group	BACTON GROUP	Bunter Sandstone Formation	LOWER GERMANIC TRIAS	Main Buntsandstein	Middle Buntsandstein	SKYTHIAN
			Bunter Shale Formation		Lower Buntsandstein	Lower	
based on Bertelsen (1980)	Eastern England Warrington et al (1980)	U.K. North Sea (Rhys 1974)		Dutch Area (NAM/RGD 1980)		Lower Saxony Warrington et al (1980)	ALPINE STAGES

Fig. 1.4 General Triassic Subdivisions Within the Study Area

Mid-North Sea High

NORTHERN DUTCH SECTOR

NORTHWEST GERMAN AREA

U.K. SECTOR

Cleaver Bank Uplift

Texel-Ijsselmeer High

SOUTHERN DUTCH SECTOR

London-Brabant Massif
(partially eroded)

Lastland—wells printed thus have been renamed to protect confidentiality. The position is only approximate

GRONINGEN

AMSTERDAM

DEN HAAG

OSNABRUCK

FIG. 1.5

Present distribution of the middle Triassic in the North Sea area, showing 'highs' where this has been totally removed due to post-Triassic erosion.

Based on Day et al (1981) and NAM/RGD (1980). Amended by the well data used in this thesis.

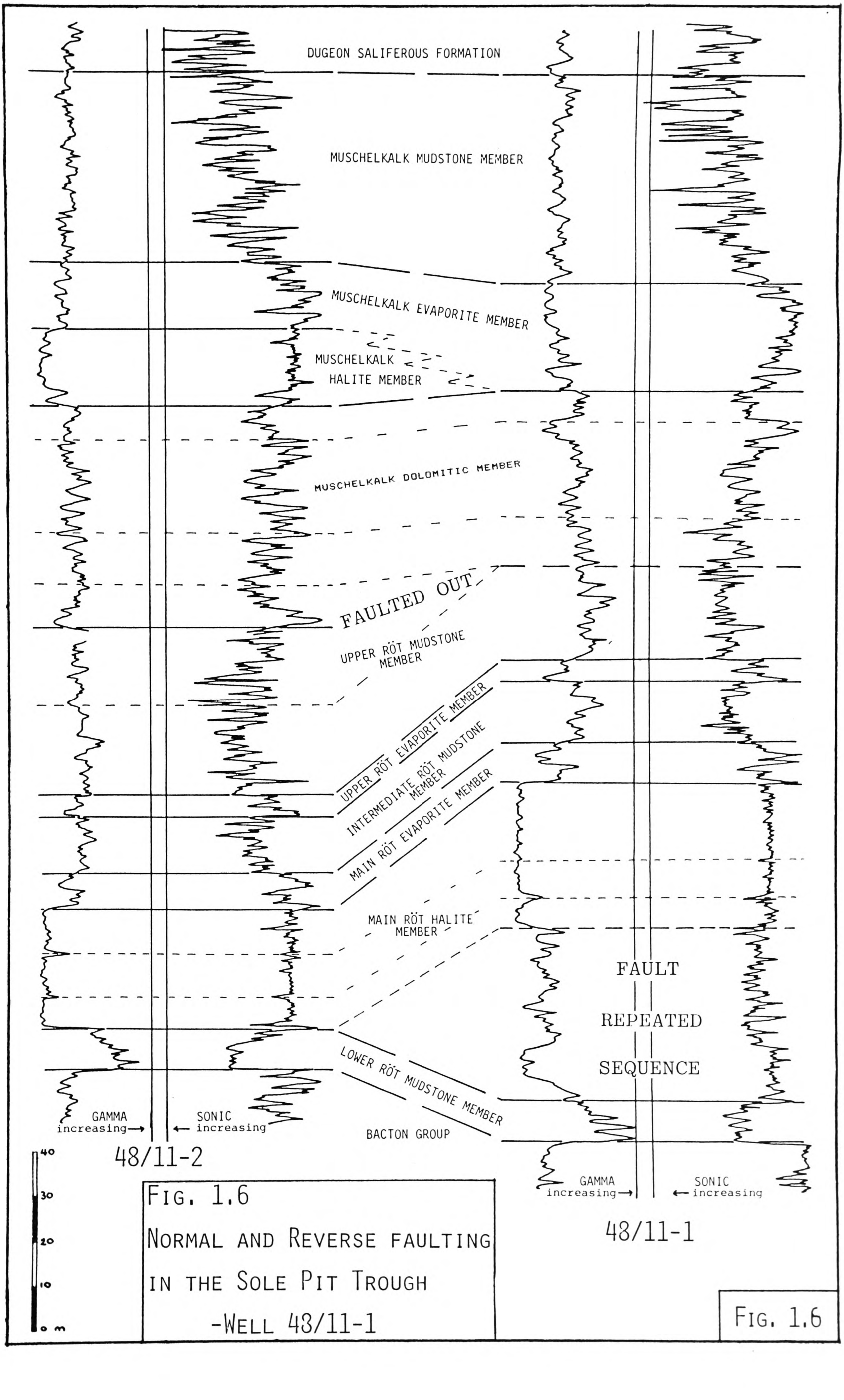
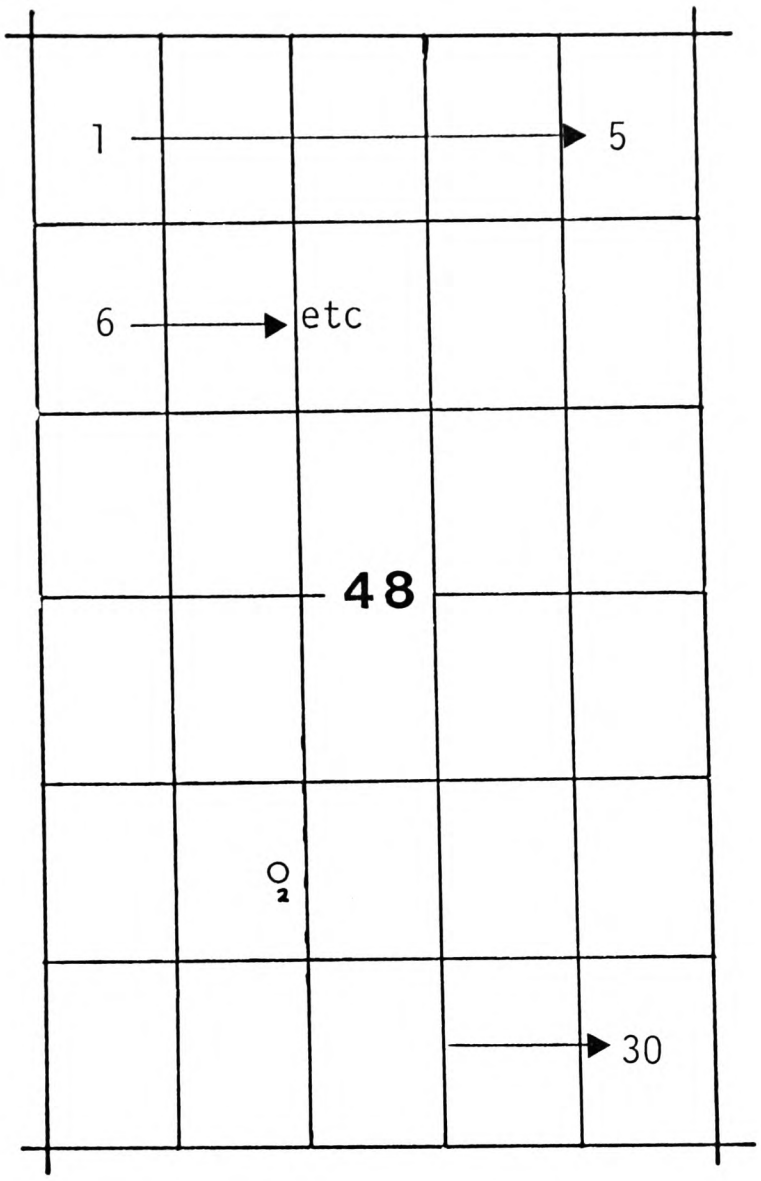


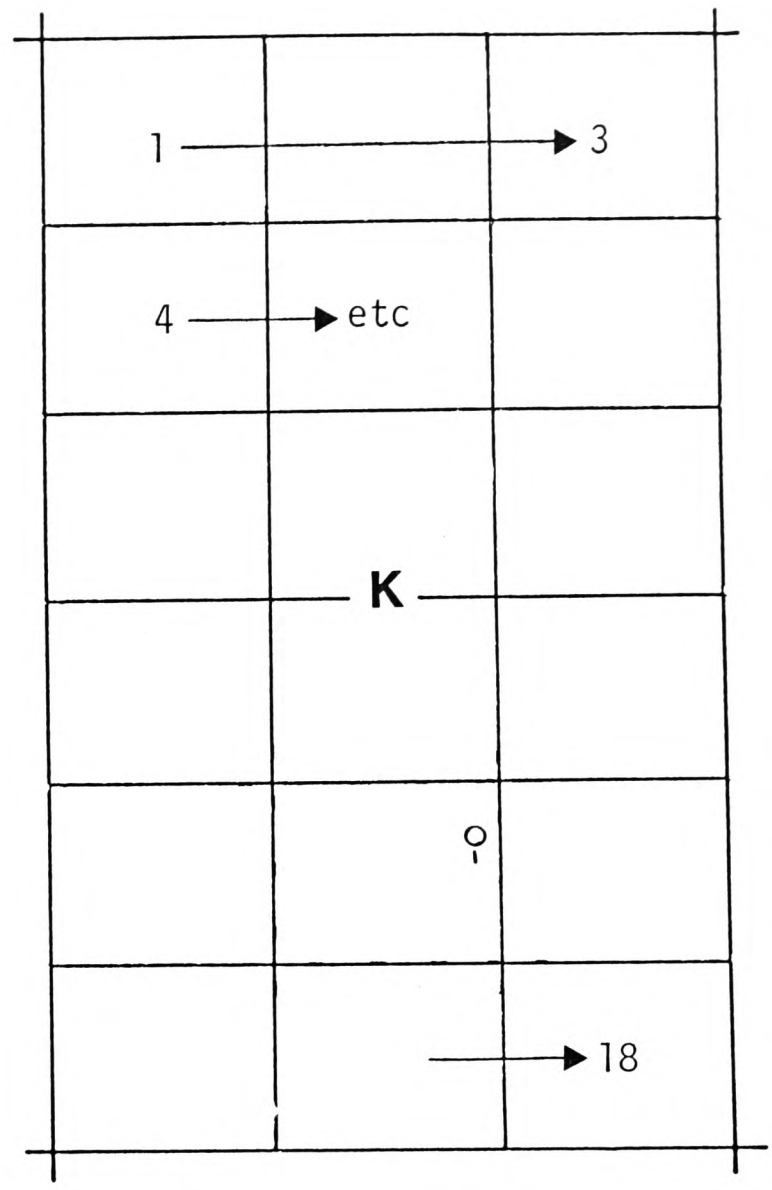
FIG. 1.6

NORMAL AND REVERSE FAULTING IN THE SOLE PIT TROUGH -WELL 48/11-1

FIG. 1.6



QUADRANT - U.K. SECTOR



QUADRANT - DUTCH SECTOR

To determine the position or name of any U.K. or Dutch well quoted in the text, or shown on any of the enclosures or diagrams:

1. Read off the quadrant number (U.K. Sector) or letter (Dutch Sector) from the map or diagram.

2. Determine the block number.
   Blocks are numbered, left to right and top to bottom, from 1 to 30 in the U.K. Sector, and 1 to 18 in the Dutch Sector. The boundaries of the blocks are shown.

3. Read off the well number from the map.

4. WELL NAME = QUADRANT / BLOCK - WELL NUMBER

   Hence the two examples above are wells 48/22-2 (U.K. Sector) and K/14-1 (Dutch Sector).

Fig. 2.1

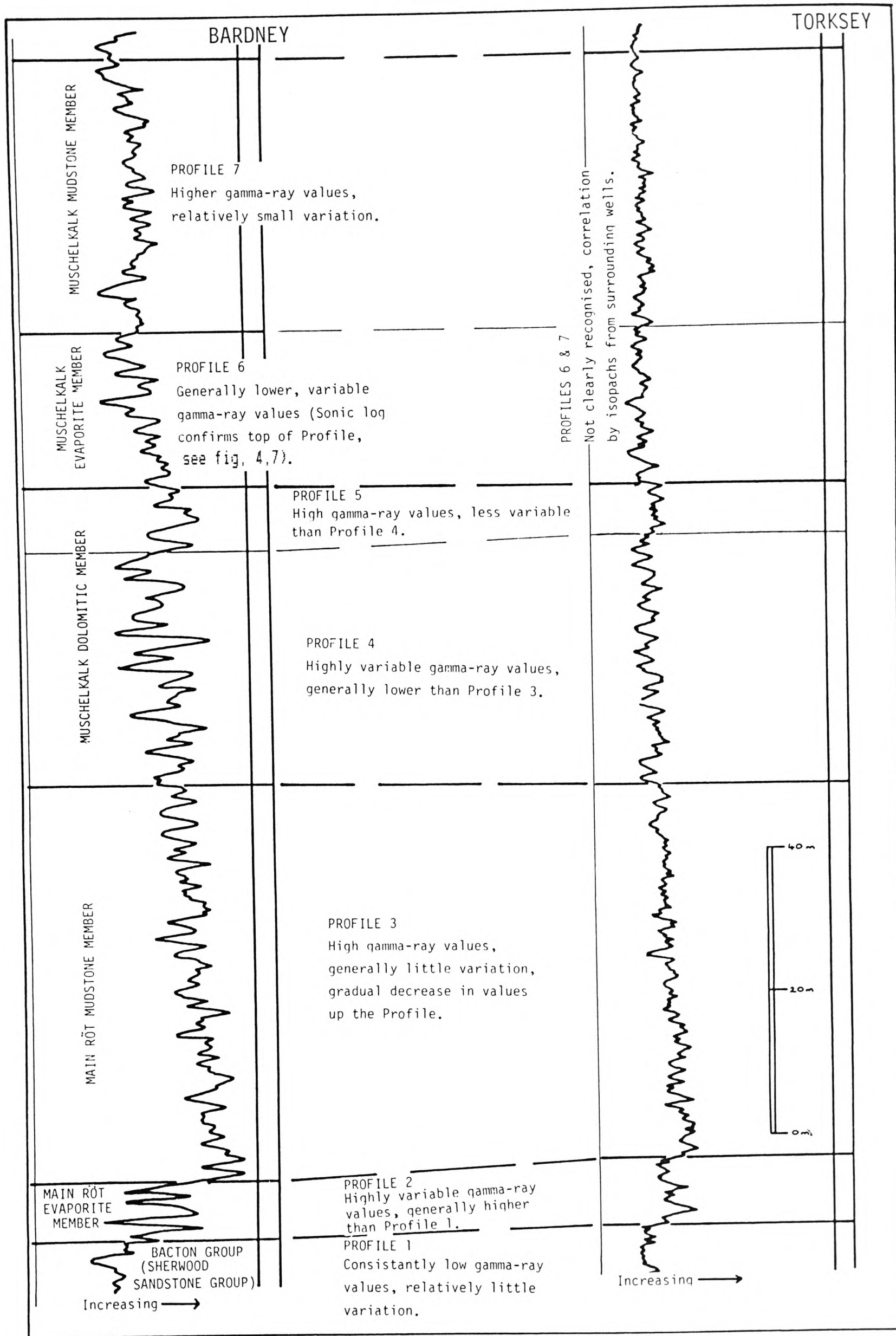


Fig. 2.2 MIDDLE TRIASSIC GAMMA-RAY CORRELATION BETWEEN CASED AND UNCASED WELLS, BASED ON THE RECOGNITION OF SIMILAR LOG PROFILES (PROFILES 1-5) OR THE ESTIMATED THICKNESS FROM ISOPACHS (PROFILES 6 & 7). THE GAMMA-RAY SCALE IS THE SAME FOR BOTH WELLS. NOTE HOW THE LITHOSTRATIGRAPHIC UNITS ARE DEFINED BY ONE OR MORE LOG PROFILES.

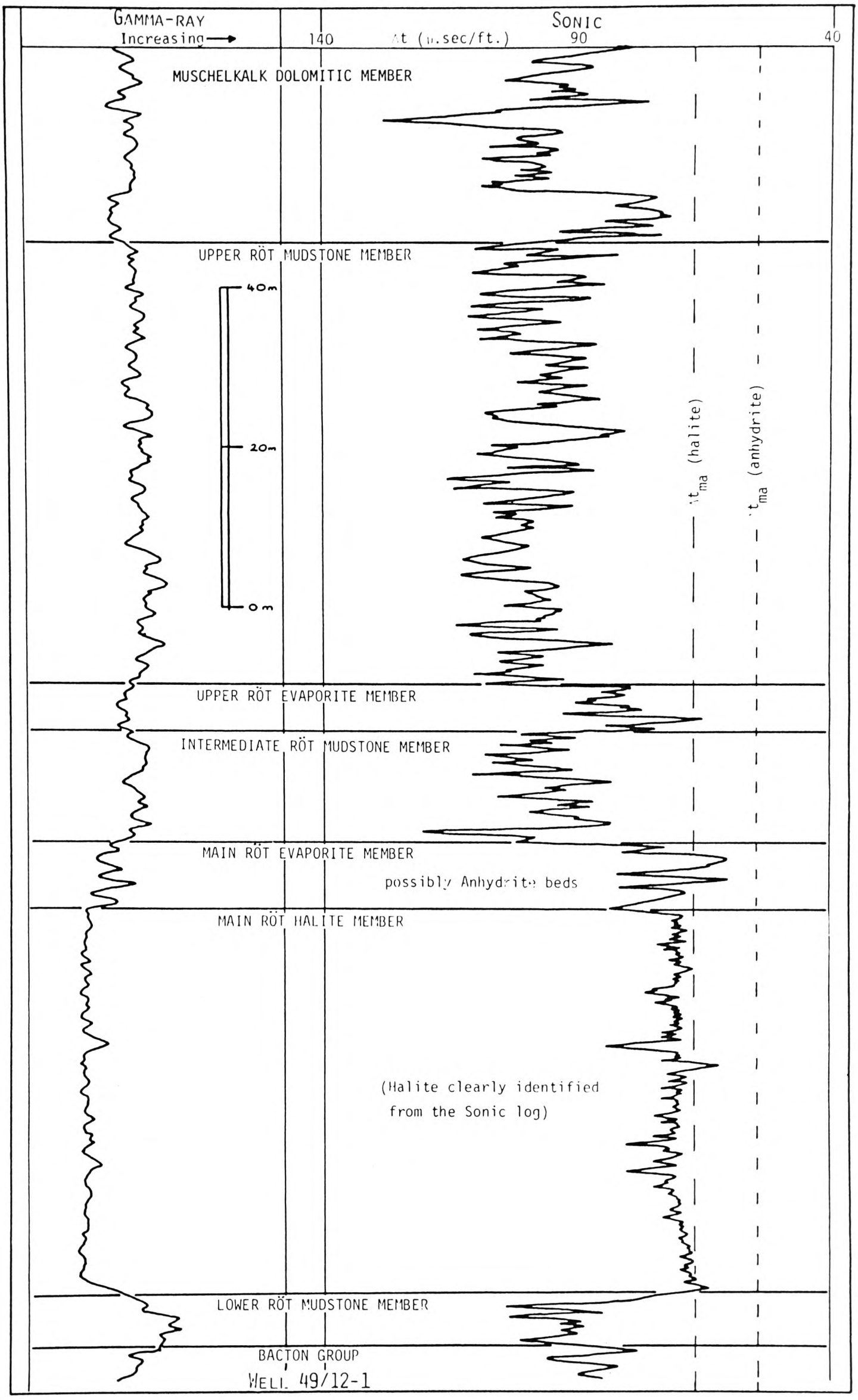


Fig. 2.3 Comparison of typical gamma-ray and sonic log profiles. The profiles of the Main Röt Evaporite Member and the Upper Röt Evaporite Member are much more distinctive on the sonic log, and likewise, the marker at the base of the Muschelkalk Dolomitic Member is better identified by its sonic log profile. Halites can be identified directly from the sonic log, and anhydrites infered.

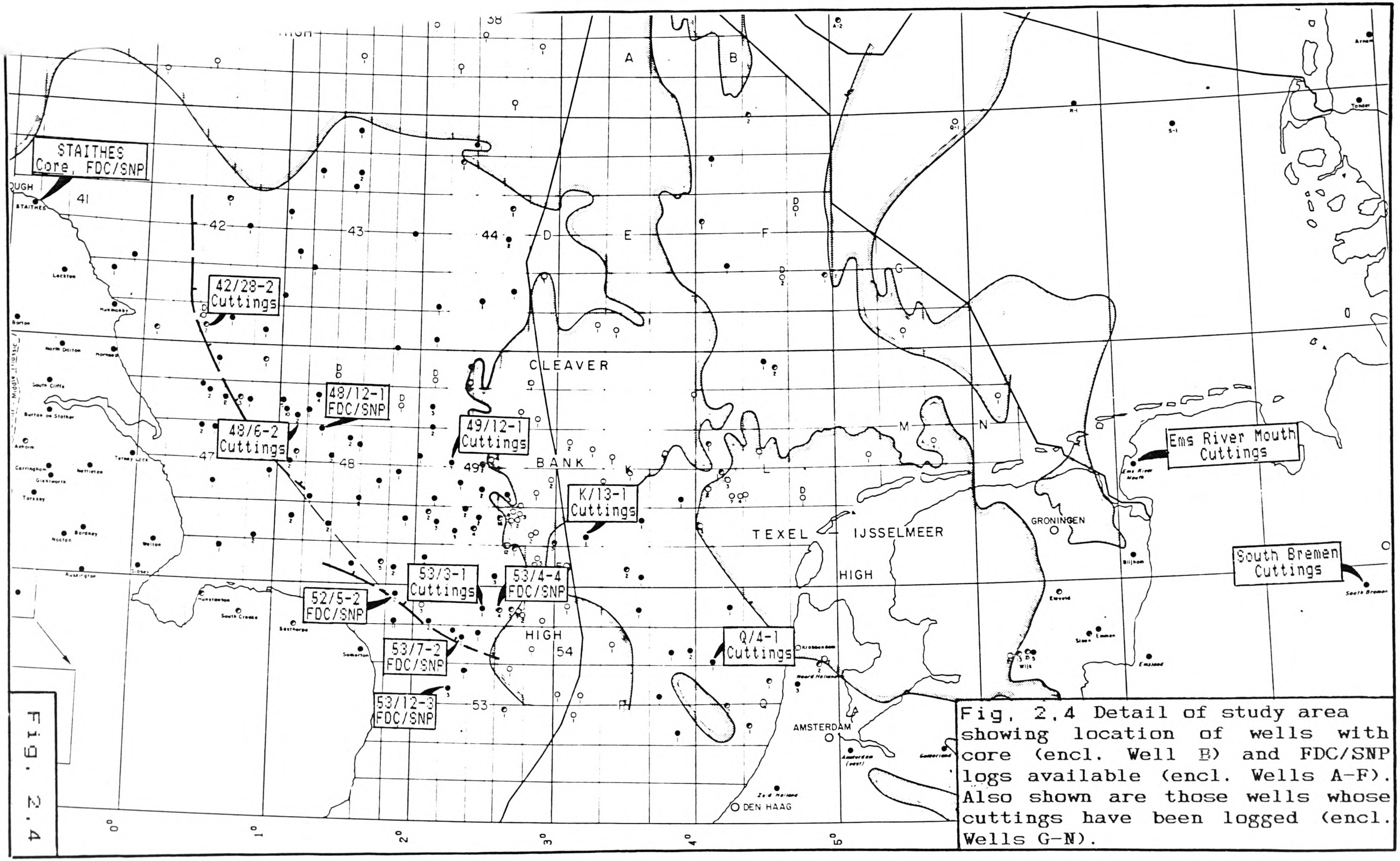


Fig. 2.4

Fig. 2.4 Detail of study area showing location of wells with core (encl. Well B) and FDC/SNP logs available (encl. Wells A–F). Also shown are those wells whose cuttings have been logged (encl. Wells G–N).

LITHOLOGY	CURVE SEPARATION	SIZE OF SEPARATION (in LPU)	ABSOLUTE SNP VALUE (in LPU)
LIMESTONE	None	zero	0 - 30
SANDSTONE	Positive	5 - 7	0 - 30
HALITE	Positive	38	≃4
DOLOMITE	Negative	8 - 13	0 - 33
ANHYDRITE	Negative	16	≃0
SHALE	Negative	10 - 30	15 - 50

Fig. 2.5 Typical lithology ranges on the FDC/SNP Cross-plot Based on Schlumberger (1974, fig. 3.3) and Prissholm and Michelsen (1979).

Fig. 2.5

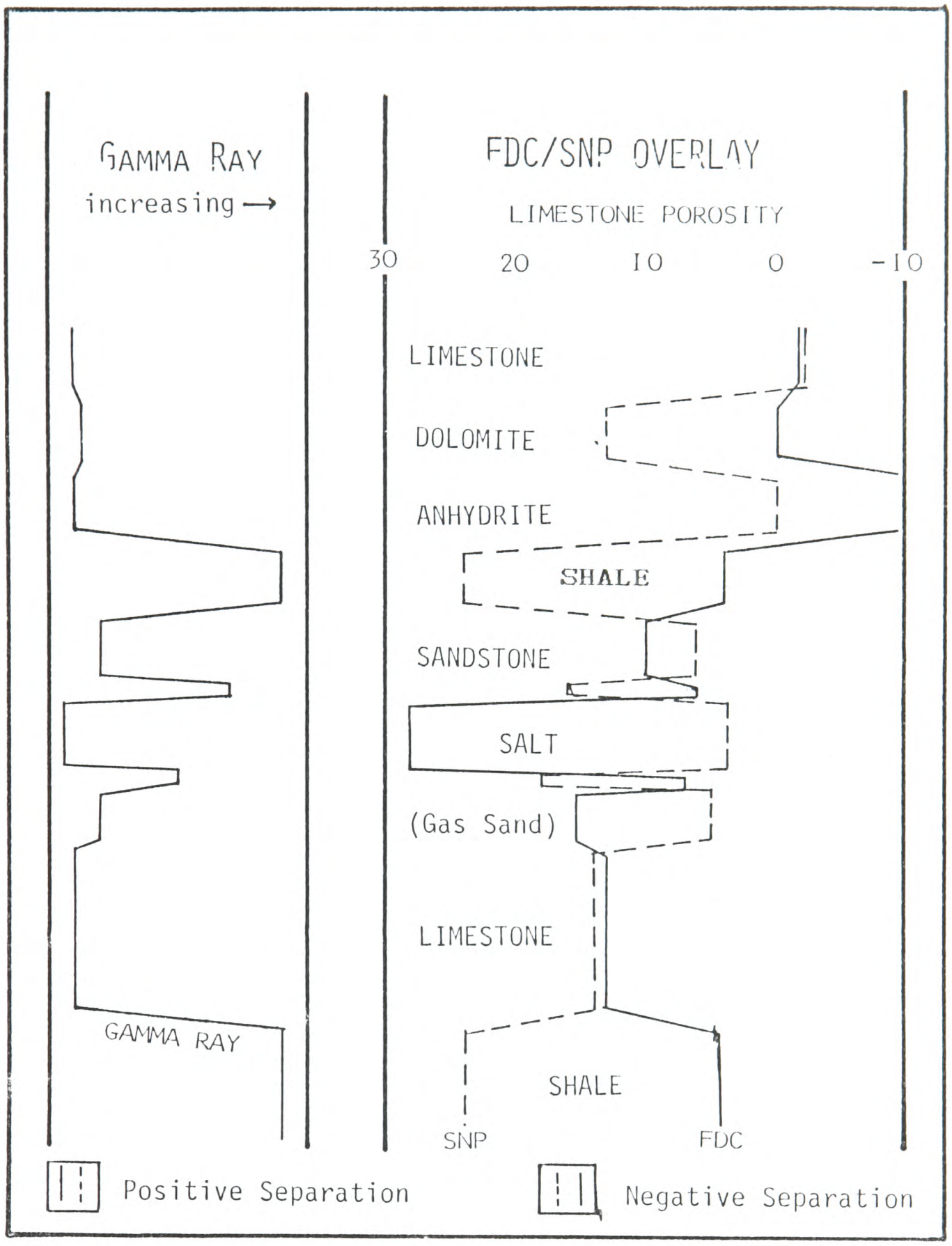


Fig. 2.6

FDC/SNP Overlay, based on Asquith and Gibson (1982, fig. 35), here adapted from the CNL to the SNP log.

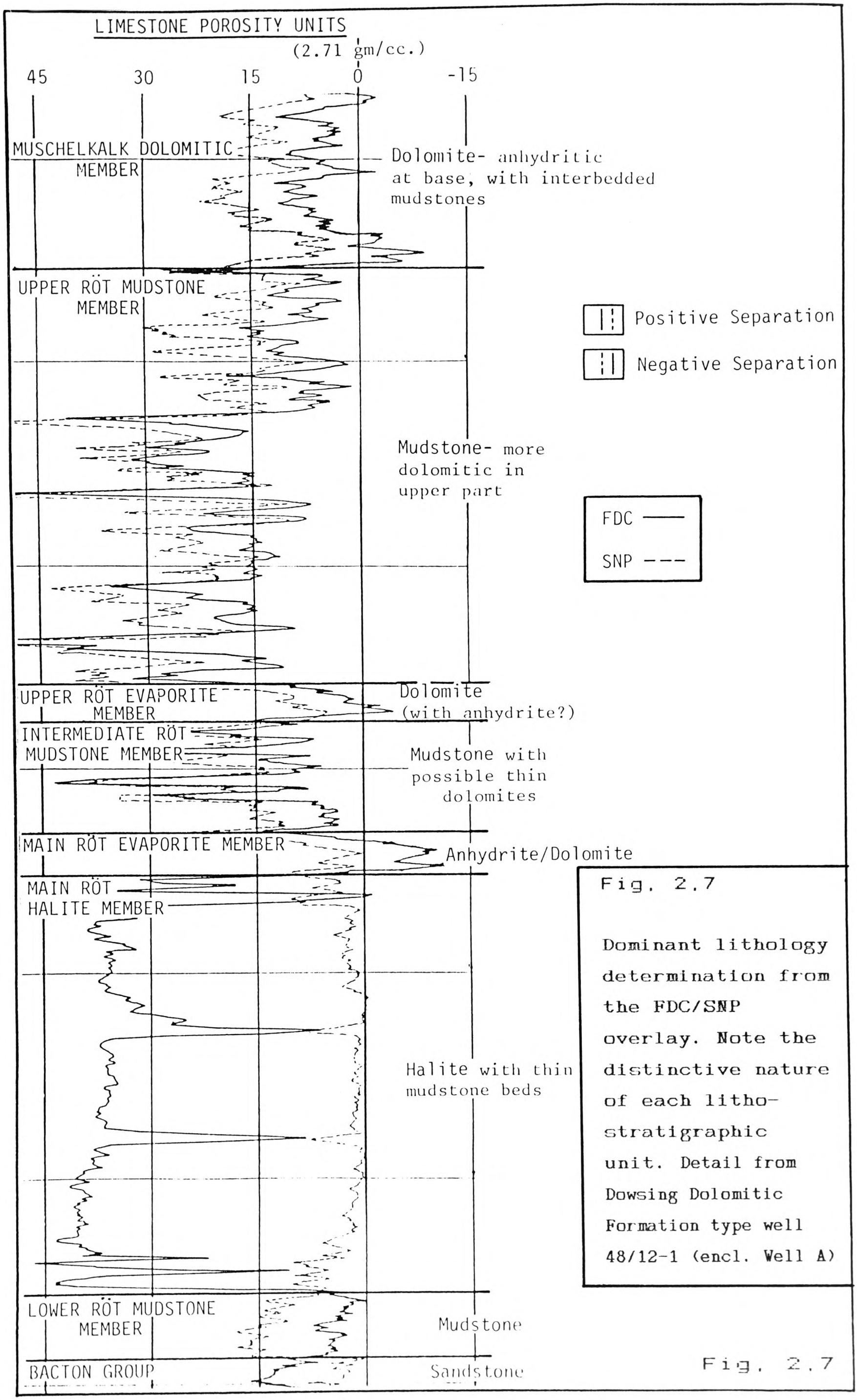
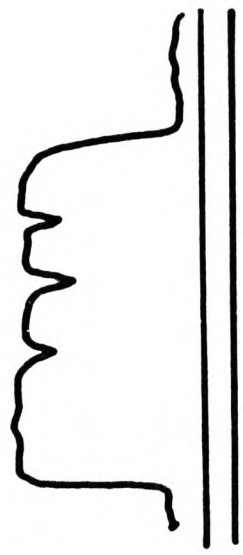


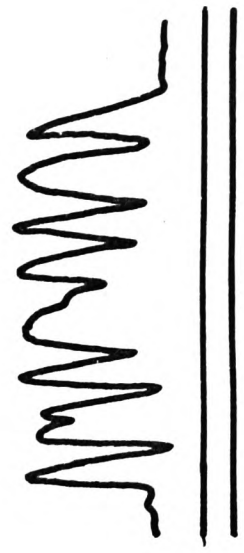
Fig. 2.7

Dominant lithology determination from the FDC/SNP overlay. Note the distinctive nature of each litho-stratigraphic unit. Detail from Dowsing Dolomitic Formation type well 48/12-1 (encl. Well A)

Fig. 2.7



BLOCKY



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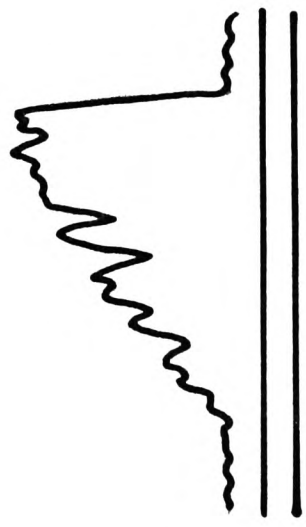
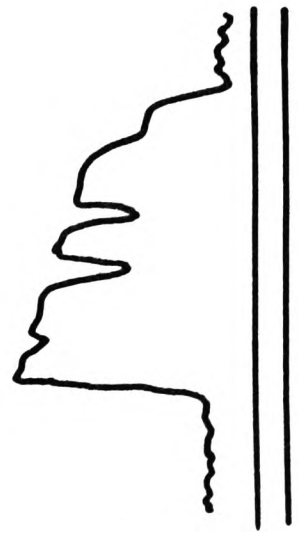


FUNNEL-SHAPED



BELL-SHAPED

Fig. 2.8
Descriptive terminology for petrophysical log profiles. The example shown is the gamma-ray log, with values increasing from left to right. The profiles are seen in mirror image for logs to the right of the well column (sonic, FDC/SNP). Based on fig. 12.5 of Rider (1986).

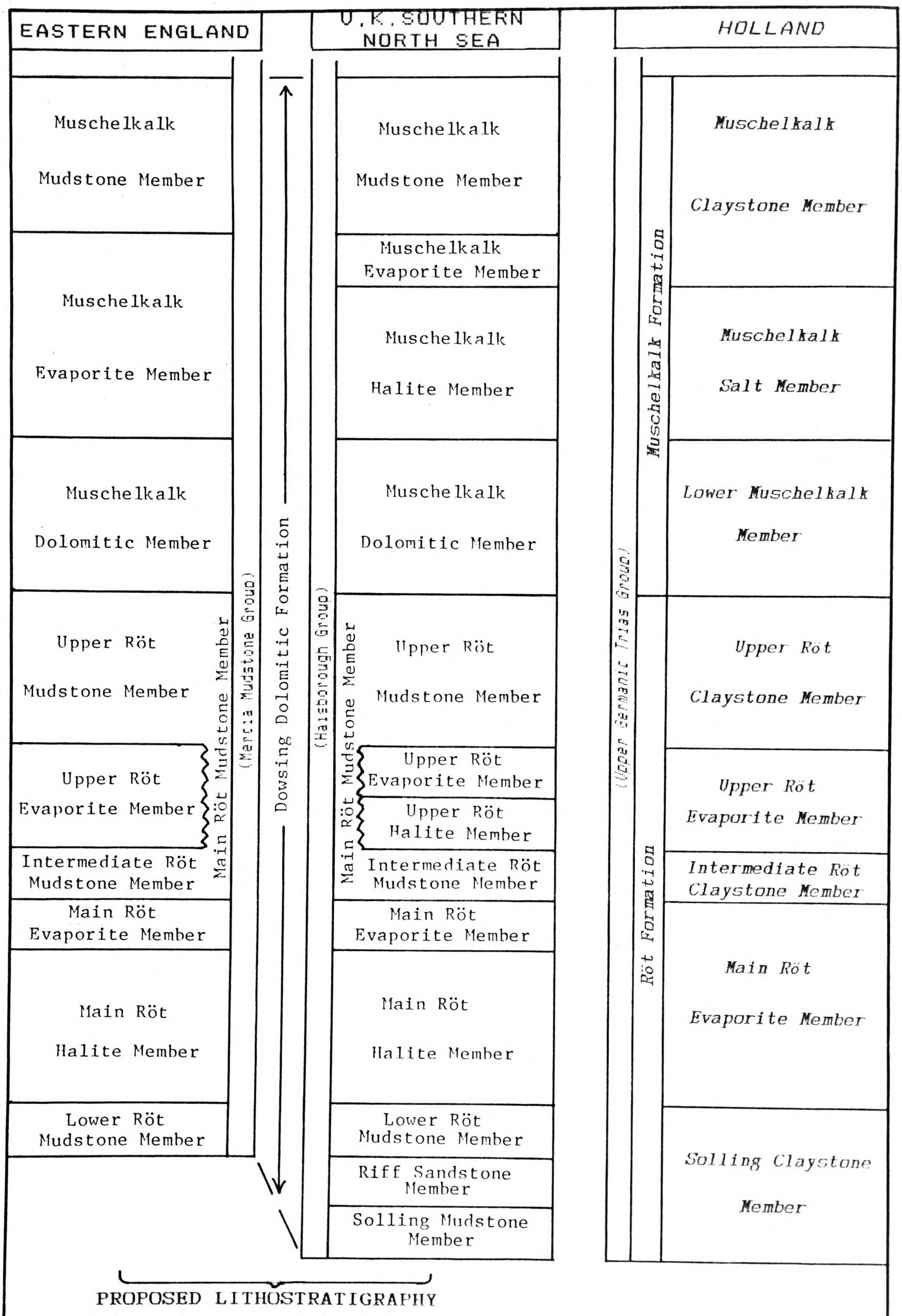


FIG. 3.1 Proposed lithostratigraphy for the U.K. Southern North Sea and eastern England. Based on the Dutch nomenclature of NAM/RGD (1990)

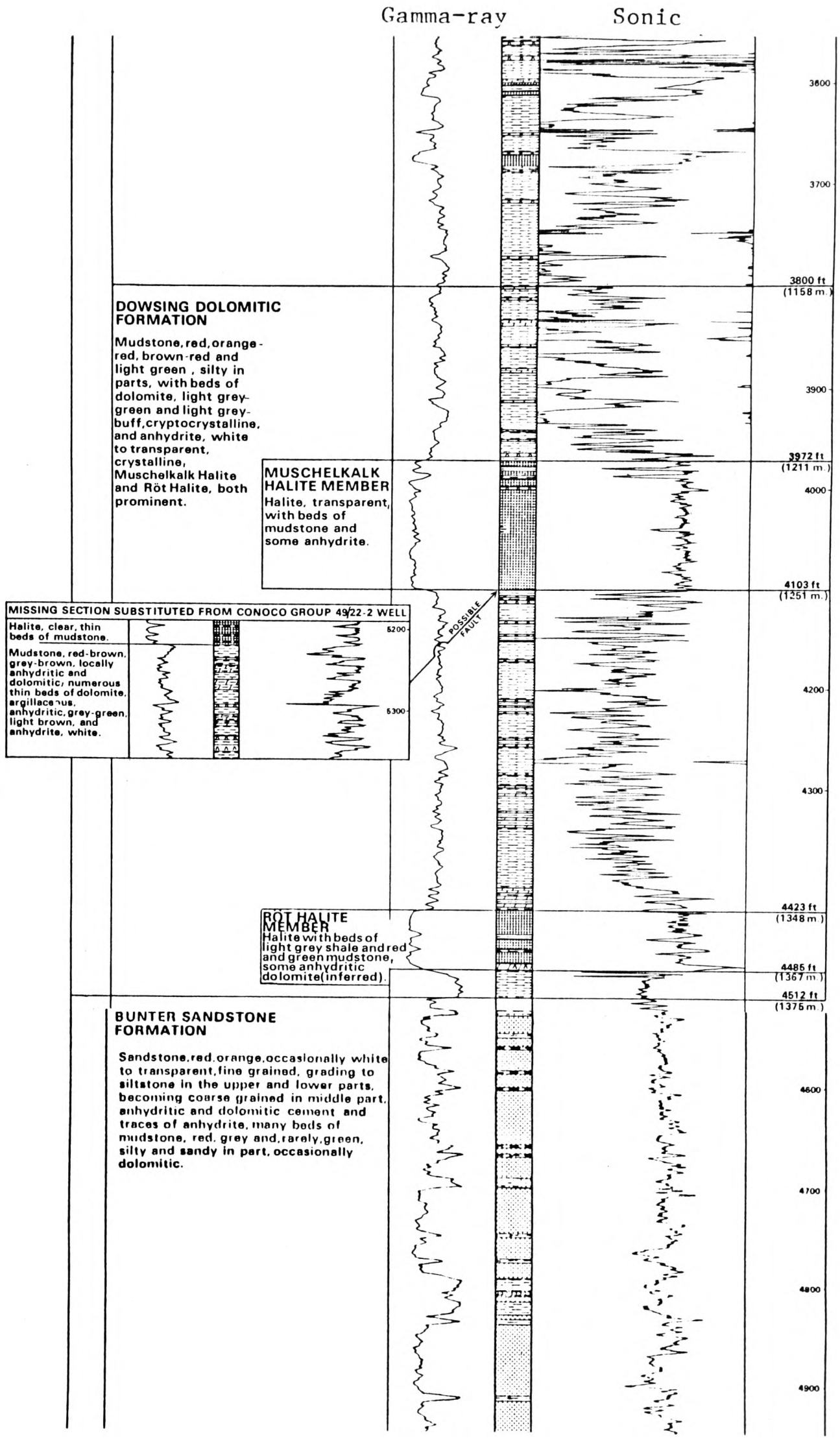


Fig. 3.2 Triassic type well 49/21-2, Detail from figs. 4 and 5 of Rhys (1974).

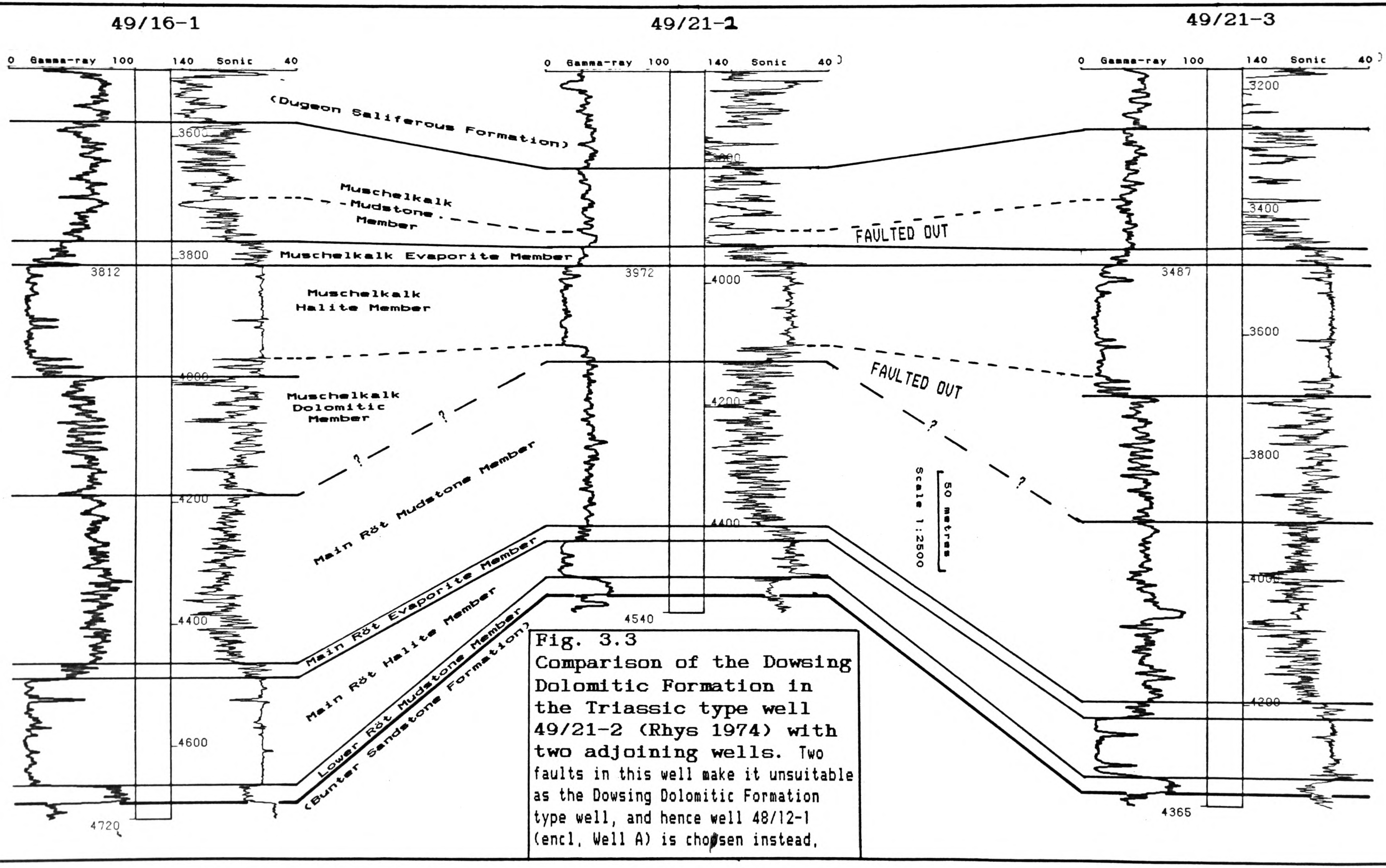


Fig. 3.3
Comparison of the Dowsing Dolomitic Formation in the Triassic type well 49/21-2 (Rhys 1974) with two adjoining wells. Two faults in this well make it unsuitable as the Dowsing Dolomitic Formation type well, and hence well 48/12-1 (encl. Well A) is chosen instead.

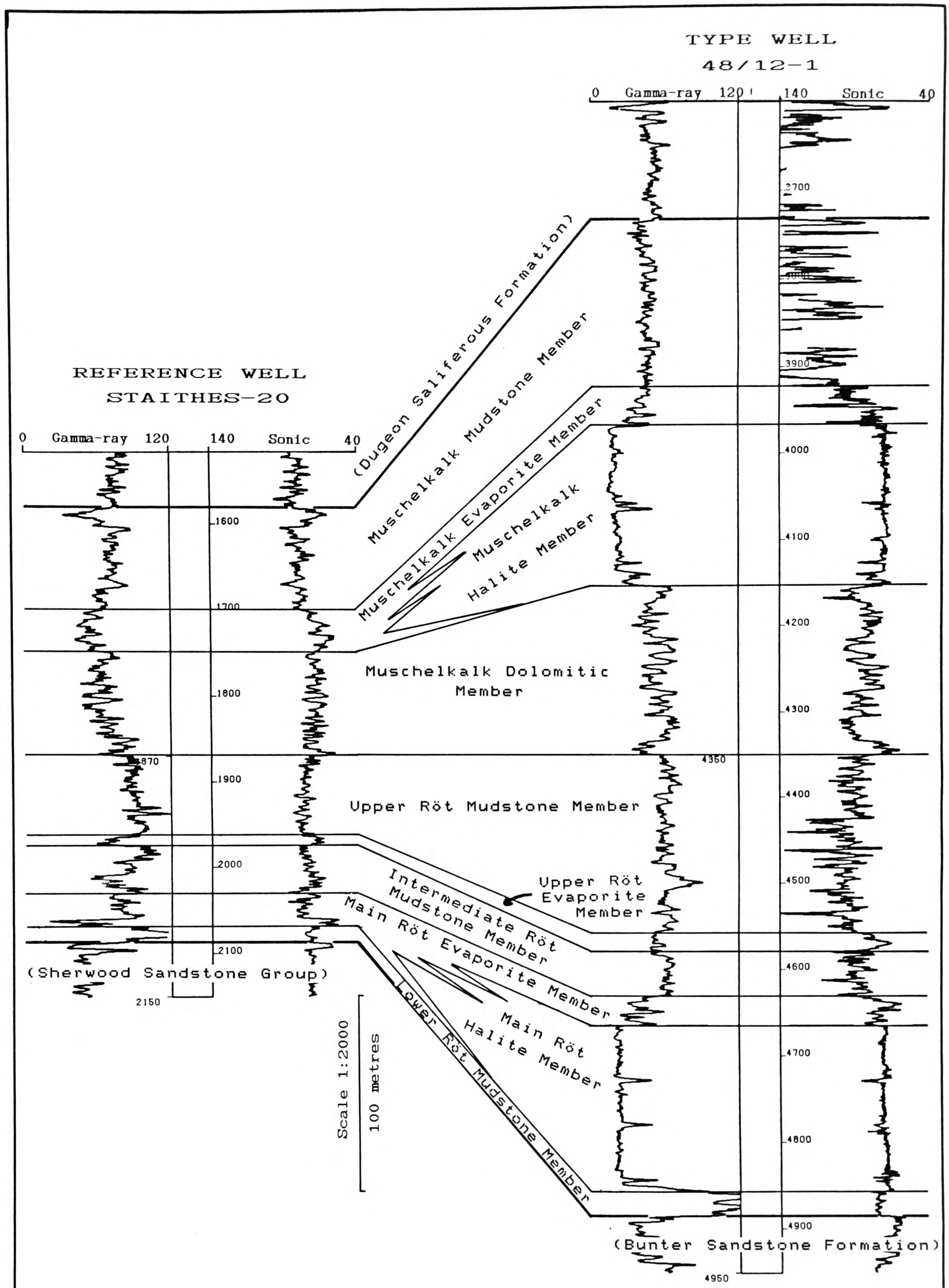


Fig.3.4
Comparison of the Dowsing Dolomitic Formation development in the type well 48/12-1 (Anglo-Dutch Basin) with that in reference well 'Staithes-20' (East Midlands Shelf). For lithologies refer to encl. Wells A and B.

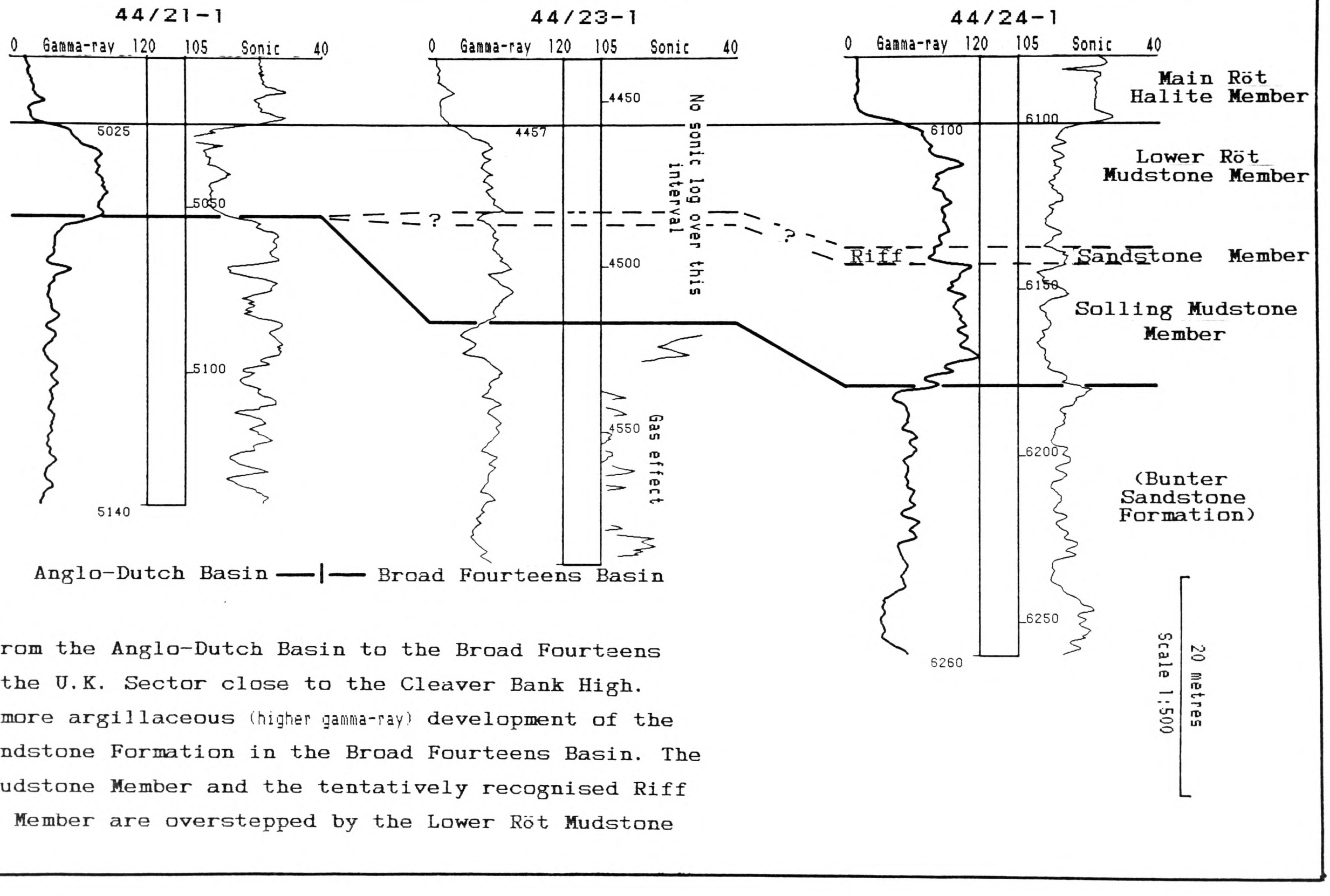


Fig. 3.5

Profile from the Anglo-Dutch Basin to the Broad Fourteens Basin in the U.K. Sector close to the Cleaver Bank High. Note the more argillaceous (higher gamma-ray) development of the Bunter Sandstone Formation in the Broad Fourteens Basin. The Solling Mudstone Member and the tentatively recognised Riff Sandstone Member are overstepped by the Lower Röt Mudstone Member.

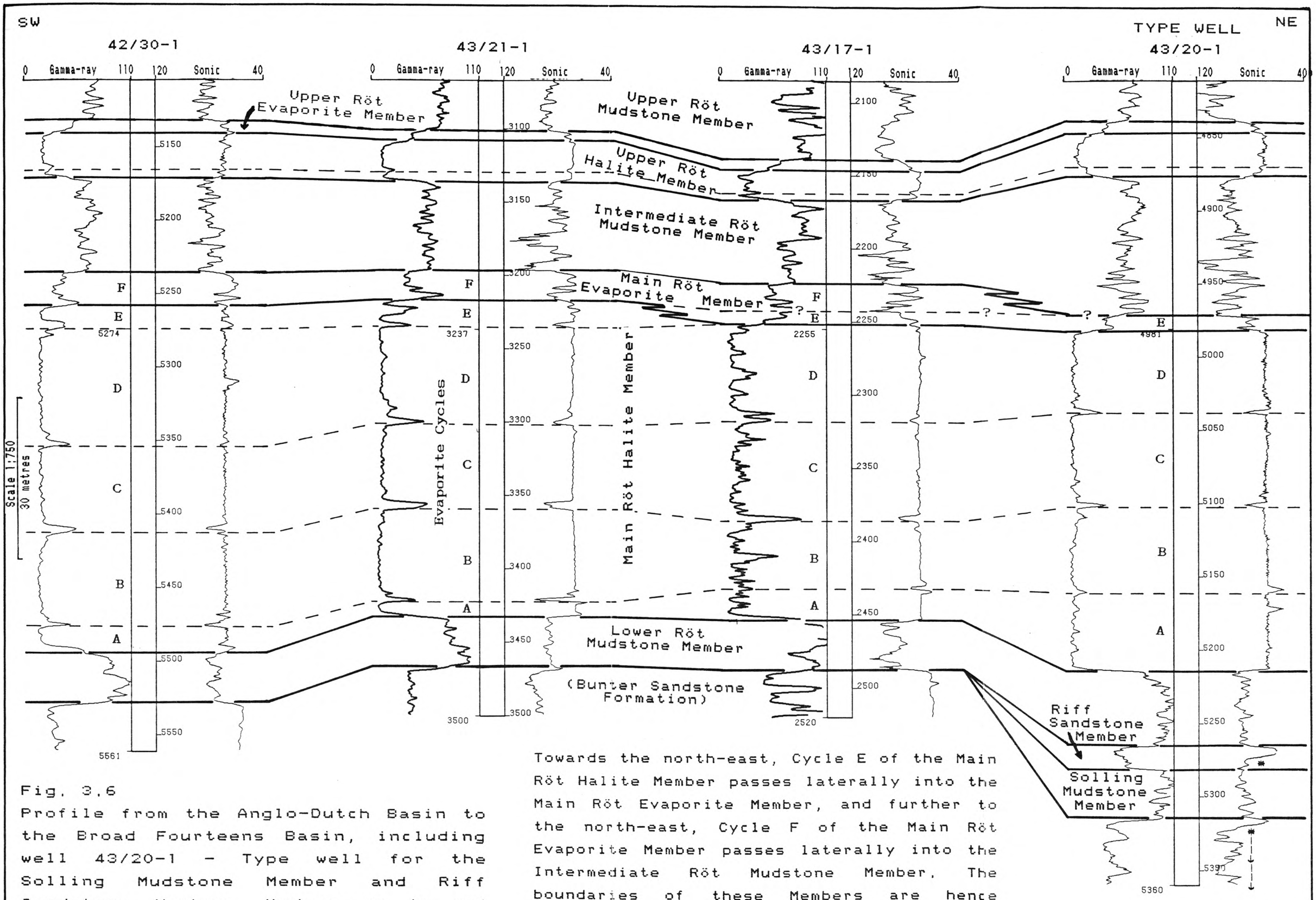


Fig. 3.6
Profile from the Anglo-Dutch Basin to the Broad Fourteens Basin, including well 43/20-1 - Type well for the Solling Mudstone Member and Riff Sandstone Member. Members up to and including Main Röt Halite Member Cycle A thicken into the Broad Fourteens Basin.

Towards the north-east, Cycle E of the Main Röt Halite Member passes laterally into the Main Röt Evaporite Member, and further to the north-east, Cycle F of the Main Röt Evaporite Member passes laterally into the Intermediate Röt Mudstone Member. The boundaries of these Members are hence diachronous. Two possible cycles are present in the Upper Röt Halite Member.

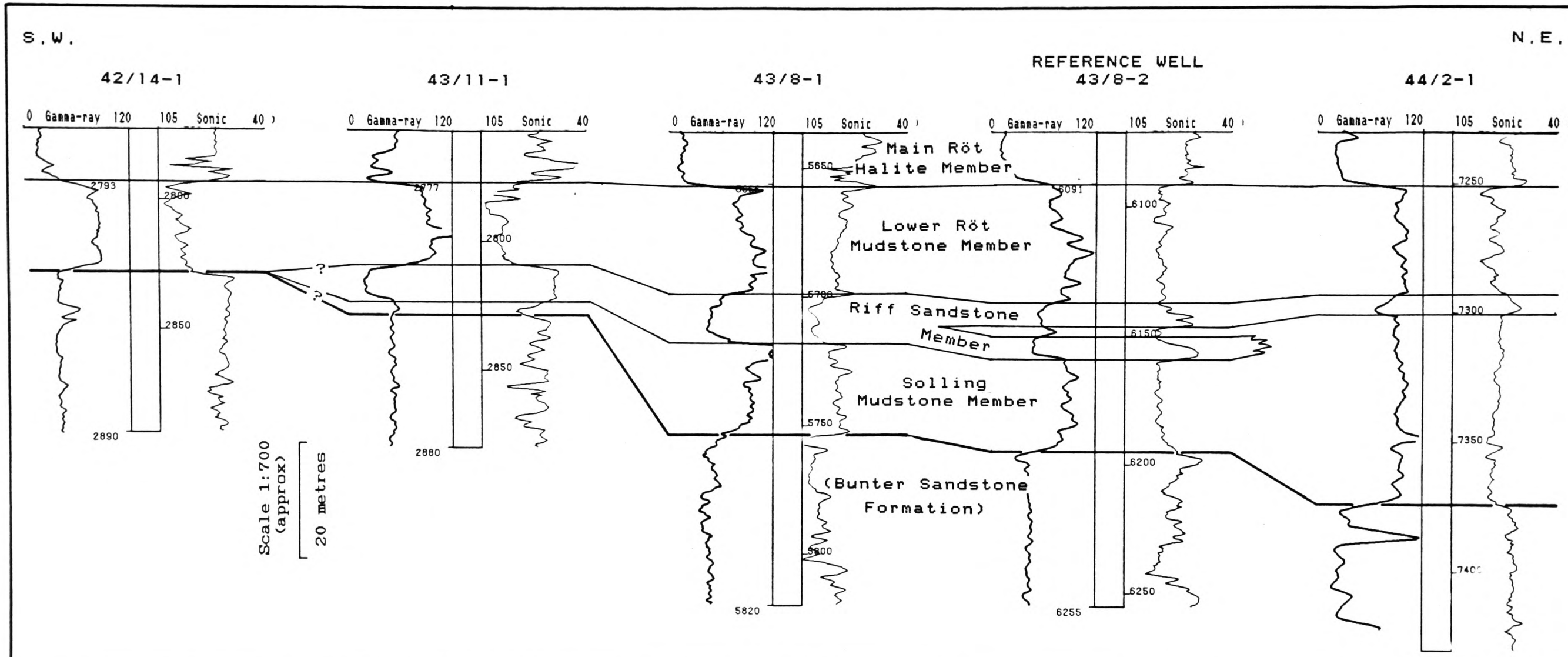


Fig. 3.7
Lowermost Members of the Dowsing Dolomitic Formation in the north-eastern part of the U.K. Southern North Sea, including Riff Sandstone Member reference well 43/8-2.

The Solling Mudstone Member thickens towards the N.E. from its margin, as does the Riff Sandstone Member. The latter Member continues to thicken in this direction due to the presence of mudstone interbeds, and then thins as individual sandstone stringers pass laterally into the Solling Mudstone Member. The Lower Röt Mudstone Member oversteps these lower Members to lie directly on the Bunter Sandstone Formation towards the S.W.

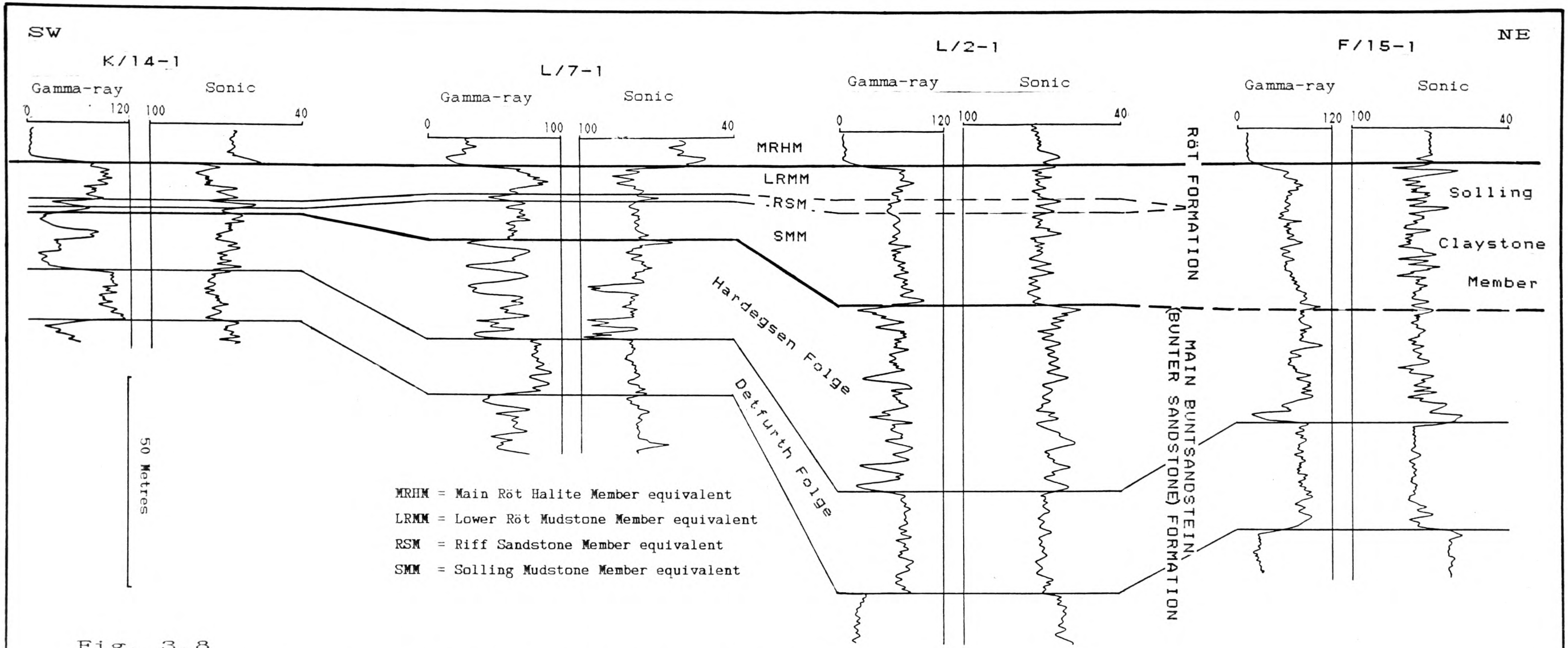


Fig. 3.8
The lower Röt Formation and the upper Main Buntsandstein Formation of the Southern Dutch Sector, showing the gradual thinning of the Solling Mudstone Member equivalent to the south-west and the Riff Sandstone Member equivalent to the north-east. The latter causes the Solling Mudstone and Lower Röt Mudstone Member equivalents to become almost indistinguishable.

In the Main Buntsandstein Formation, the Hardegsen Folge becomes increasingly argillaceous towards the north-east, resulting in a poorly defined boundary with the Solling Claystone Member.

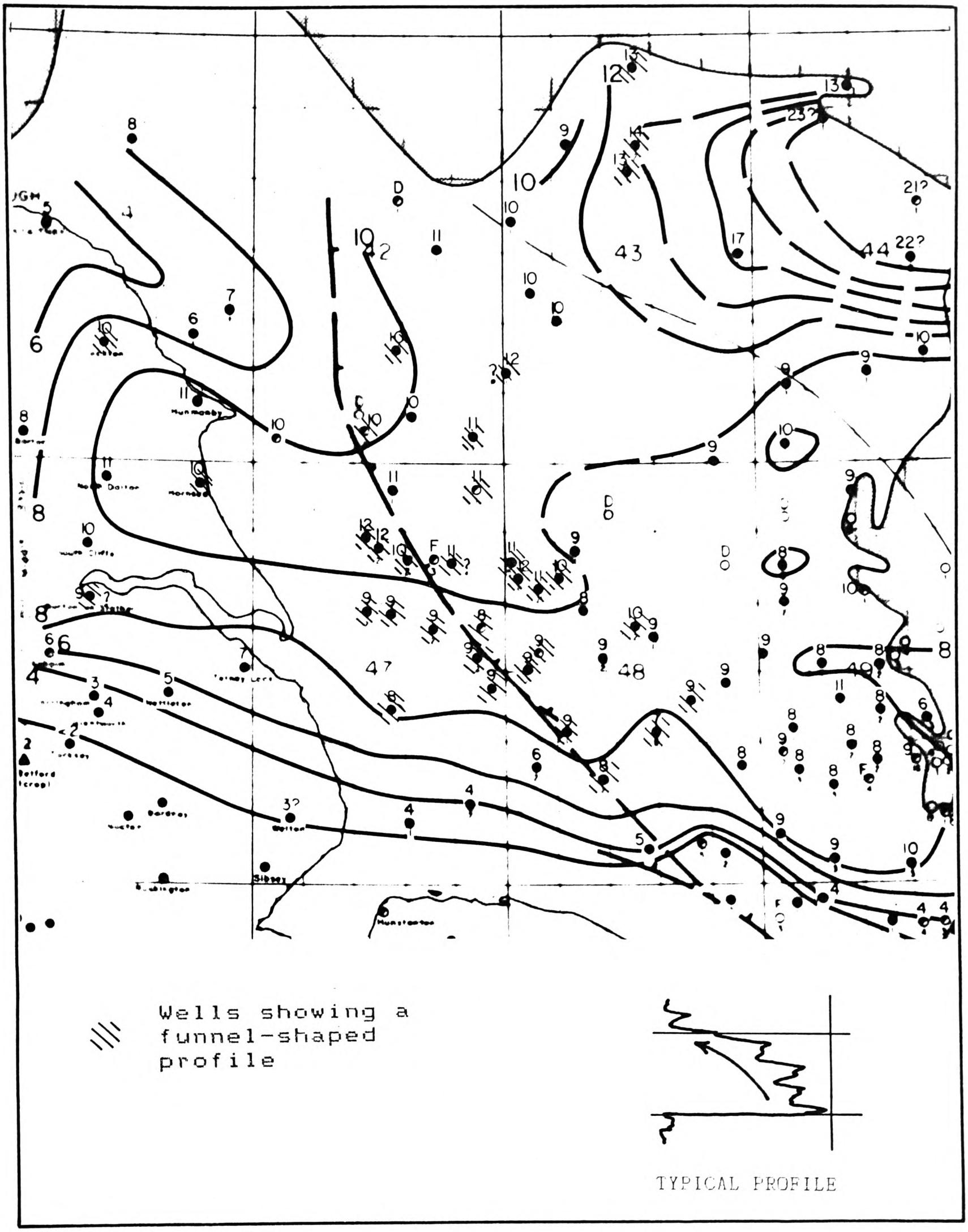
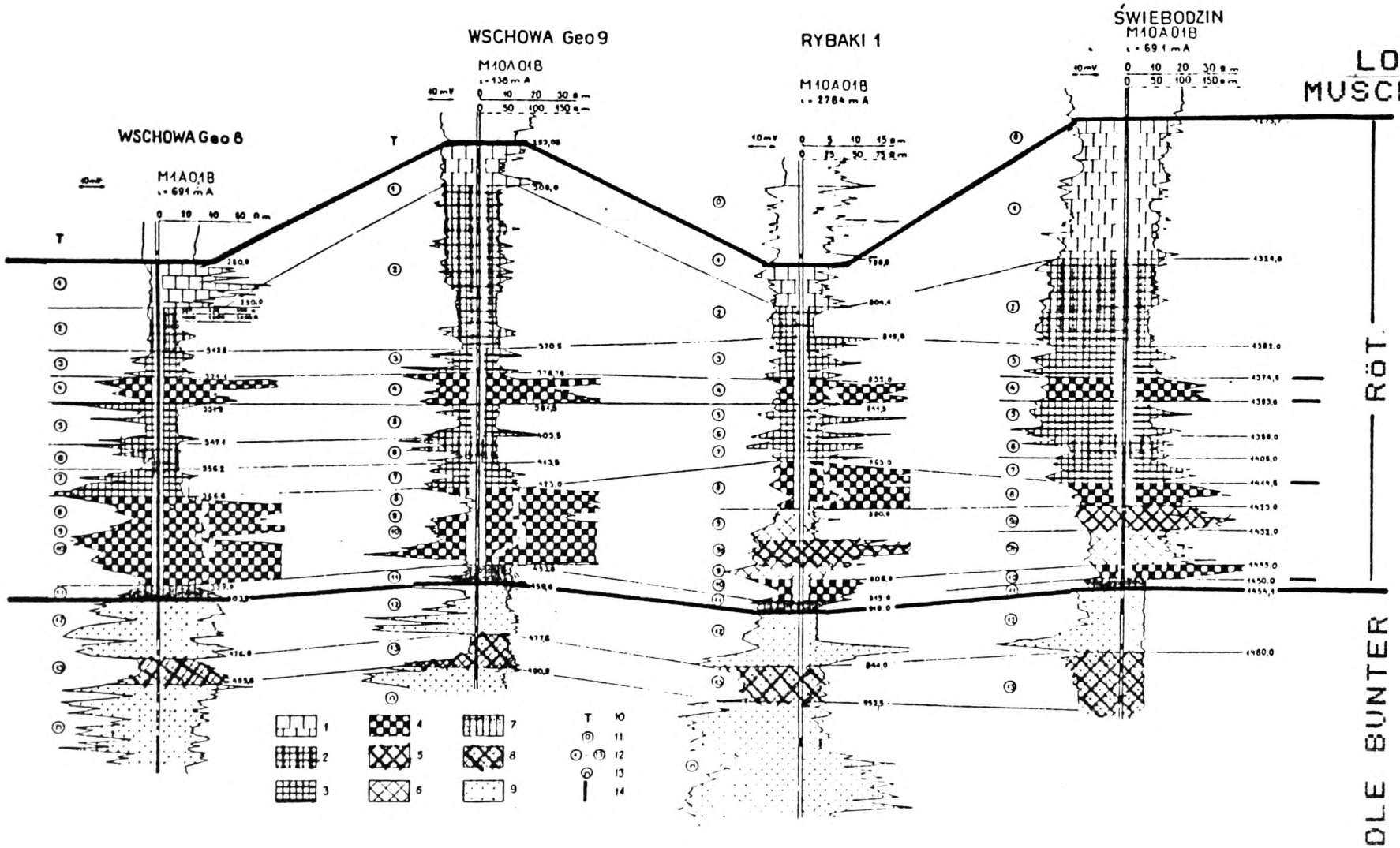


Fig. 3.9
Distribution of wells showing an asymetrical, funnel-shaped gamma-ray profile in the Lower Röt Mudstone Member of the U.K. Southern North Sea area (superimposed on a detail of encl. Map 4). This profile is restricted, in the main, to the area around the Dowsing Fault Zone.



LITHOLOGIES: 1, Limestone + Marl; 2, Limestone + Marl + Dolomite + Dolomitic Marl; 3, Dolomite + Dolomitic Marl; 4, Anhydrite; 5, Anhydrite + Halite; 6, Halite; 7, Red/Green Mudstone; 8, Red/Green Mudstone - Sandstone; 9, Sandstone

Fig. 3,10
Electric (resistivity) log profiles for the Röt succession of Poland (fig. 4 of Tokarski (1965)).

Note the similarity with the U.K. succession some 1000 km to the west. The Middle Bunter is overlain by a 6 metre thick red/green mudstone (Lower Röt Mudstone Member equivalent?), which in turn is overlain by an anhydritic, locally halitic unit (Main Röt Halite/ Evaporite Member equivalent). Approximately 29 metres above this is a second, thinner anhydritic unit (Upper Röt Evaporite Member equivalent).

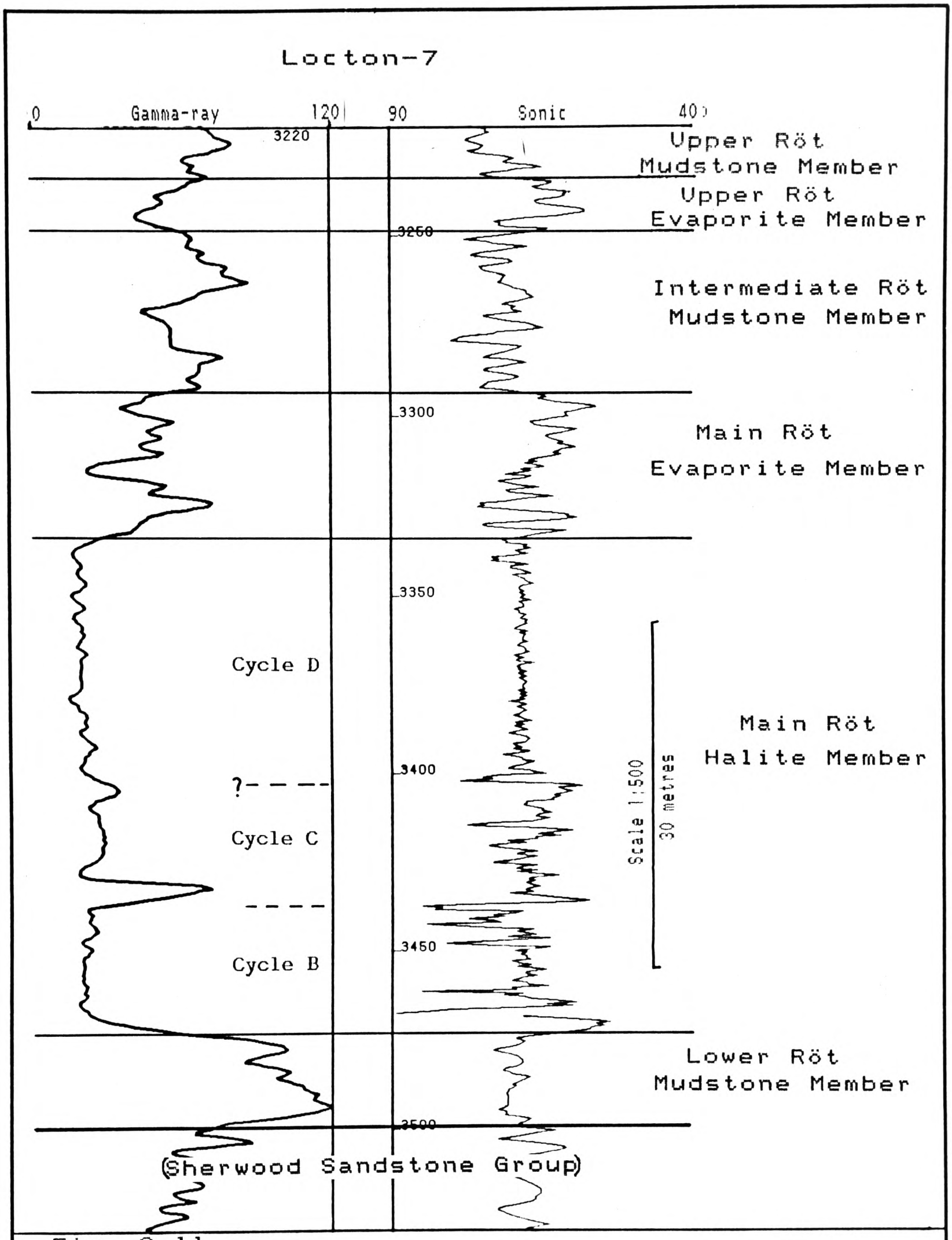


Fig. 3.11

LOCTON-7 - reference well for the Main Röt Halite Member of the Dowsing Dolomitic Formation of the Mercia Mudstone Group in the subsurface of eastern England.

The basinwide halite cycles can be tentatively recognised, the lower two containing many interbedded anhydrites and mudstones (serrated sonic log), while the upper is relatively pure.

The underlying Lower Röt Mudstone Member shows an example of a decreasing upwards gamma-ray profile.

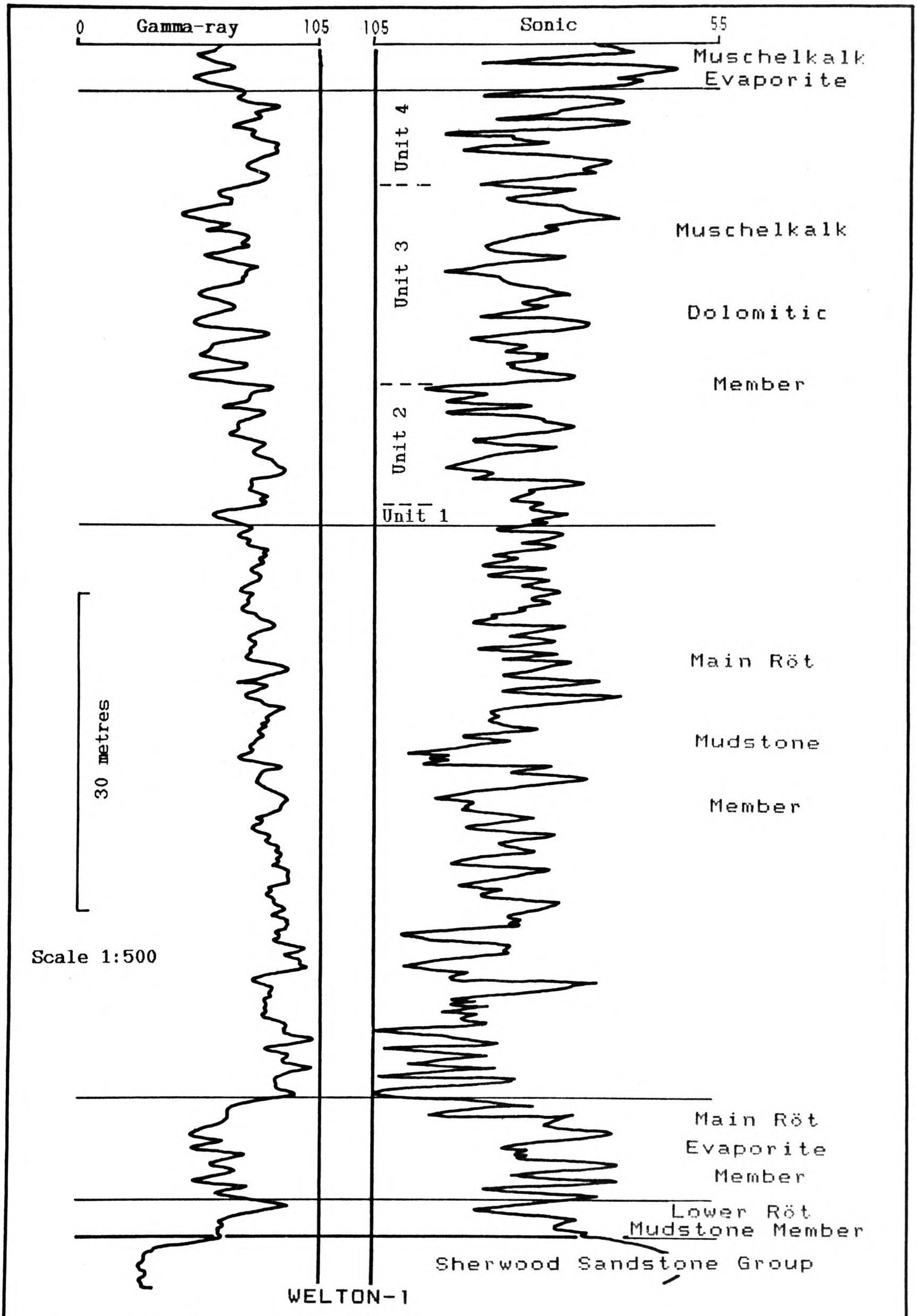


Fig. 3.12

Welton-1 well. Reference well for the Main Röt Evaporite Member and the Main Röt Mudstone Member of the Dowsing Dolomitic Formation of the Mercia Mudstone Group in the subsurface eastern England.

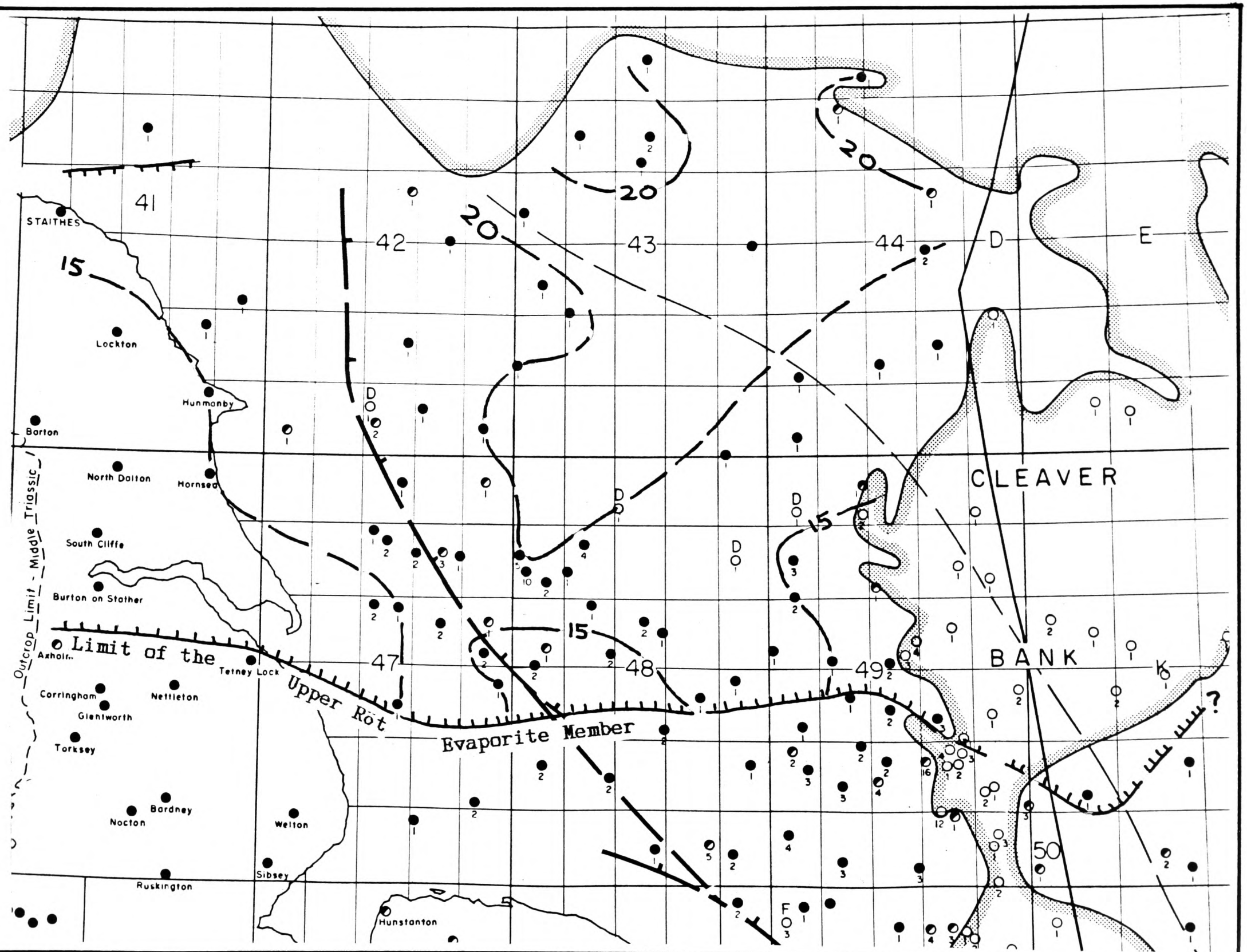
Fig. 3.13

Isopach map of the Intermediate Röt Mudstone Member in the U.K. Southern North Sea area.

Thickness in individual wells is listed in Appendix A, Table 1

Scale 1:1,500,000

Isopachs in metres



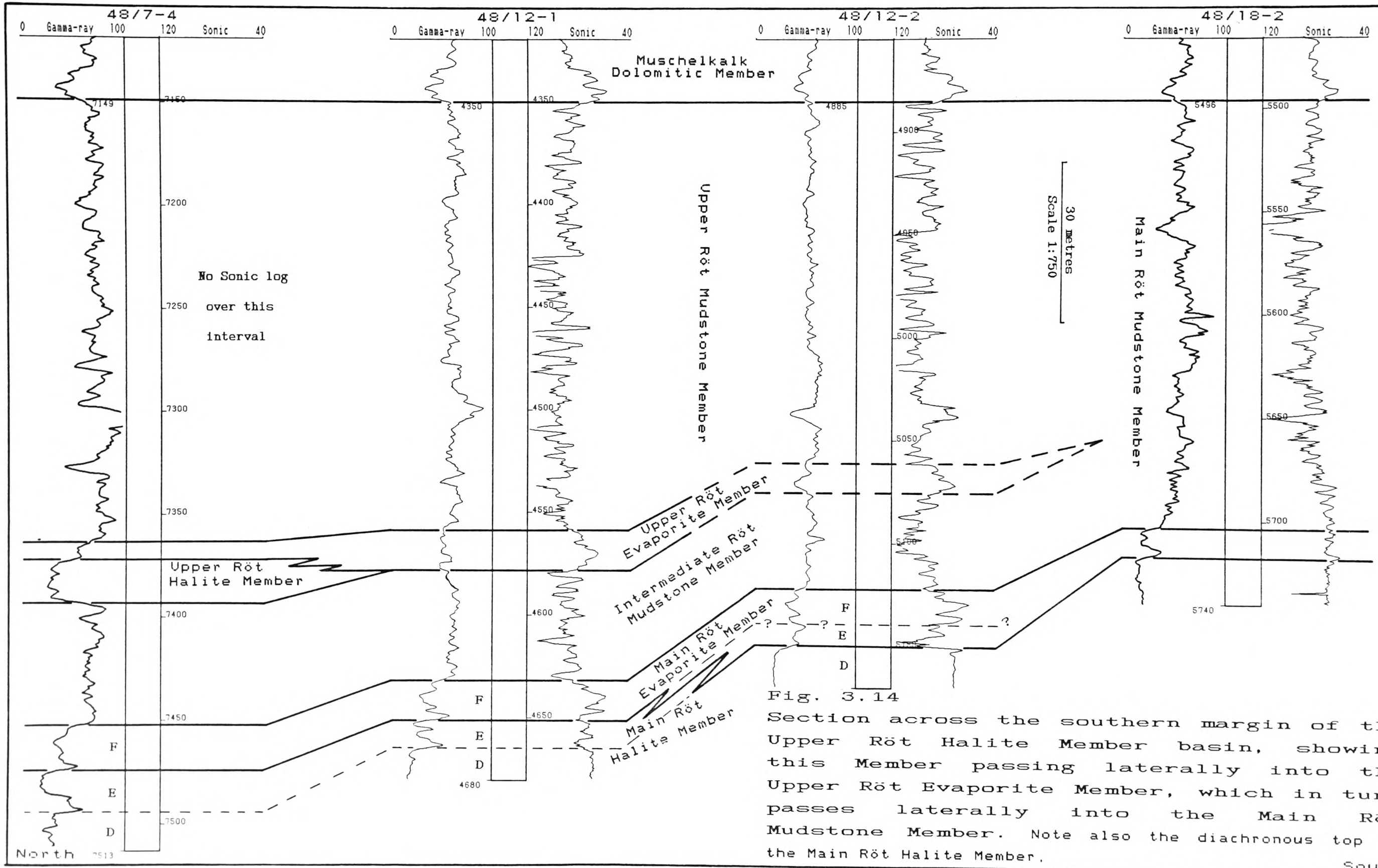


Fig. 3.14
Section across the southern margin of the Upper Röt Halite Member basin, showing this Member passing laterally into the Upper Röt Evaporite Member, which in turn passes laterally into the Main Röt Mudstone Member. Note also the diachronous top to the Main Röt Halite Member.

West

East

East Midlands Shelf → ← Anglo-Dutch Basin

TYPE WELL
(Reference Well)
49/26-4

48/28-1

48/30-2

Muschelkalk Mudstone Member

Muschelkalk Evaporite Member

Muschelkalk Halite Member

Muschelkalk Dolomitic Member

Unit 4

Unit 3

Unit 2

Unit 1

Main Röt Mudstone Member

Main Röt Evaporite Member

Scale 1:1000
30 metres

* - - * Possible correlative horizon within the Muschelkalk Halite Member

Fig. 3.15
Profile from the East Midlands Shelf into the Anglo-Dutch Basin in the southern part of the U.K. Sector, including Main Röt Mudstone Member type well 49/26-4. This well also serves as a reference well for the Muschelkalk Halite Member.

The four-fold division of the Muschelkalk Dolomitic Member is recognised in these wells, but in this southern part of the U.K. Sector, Unit 1 is more difficult to recognise. Thin mudstones are common in the Muschelkalk Halite Member but, unlike the Main Röt Halite Member, they are difficult to correlate between wells. One particular halite (marked *) can be recognised in many (although not all) wells.

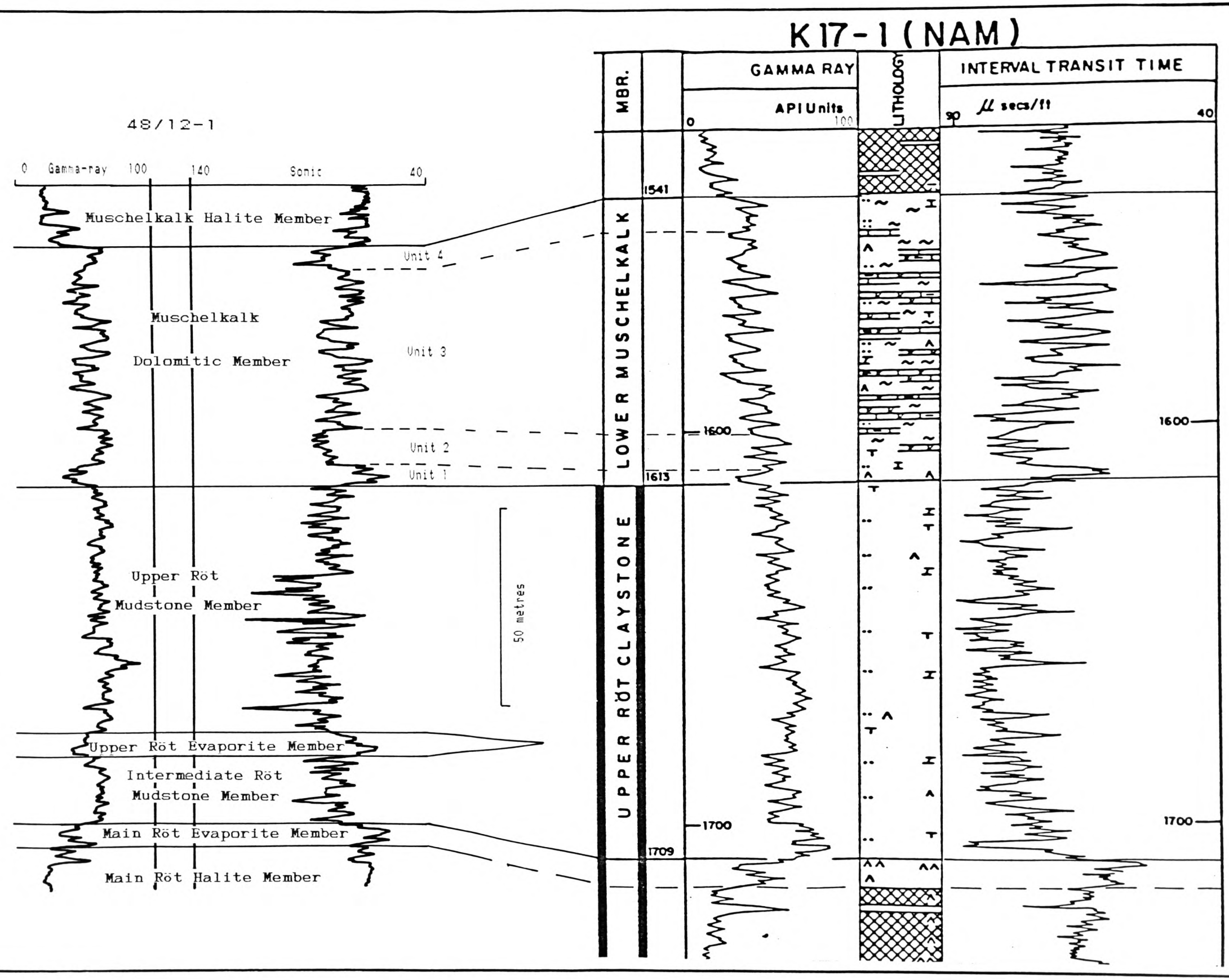


Fig. 3.16 Comparison of the Röt/Muschelkalk boundary in the U.K. and Dutch Sectors (Dowsing Dolomitic Formation type well 48/12-1 and Dutch well K/17-1 (latter from encl. 9 of NAM/RGD 1980)). This boundary is easily identified in the U.K. Sector, despite assertions to the contrary (Rhys 1975).

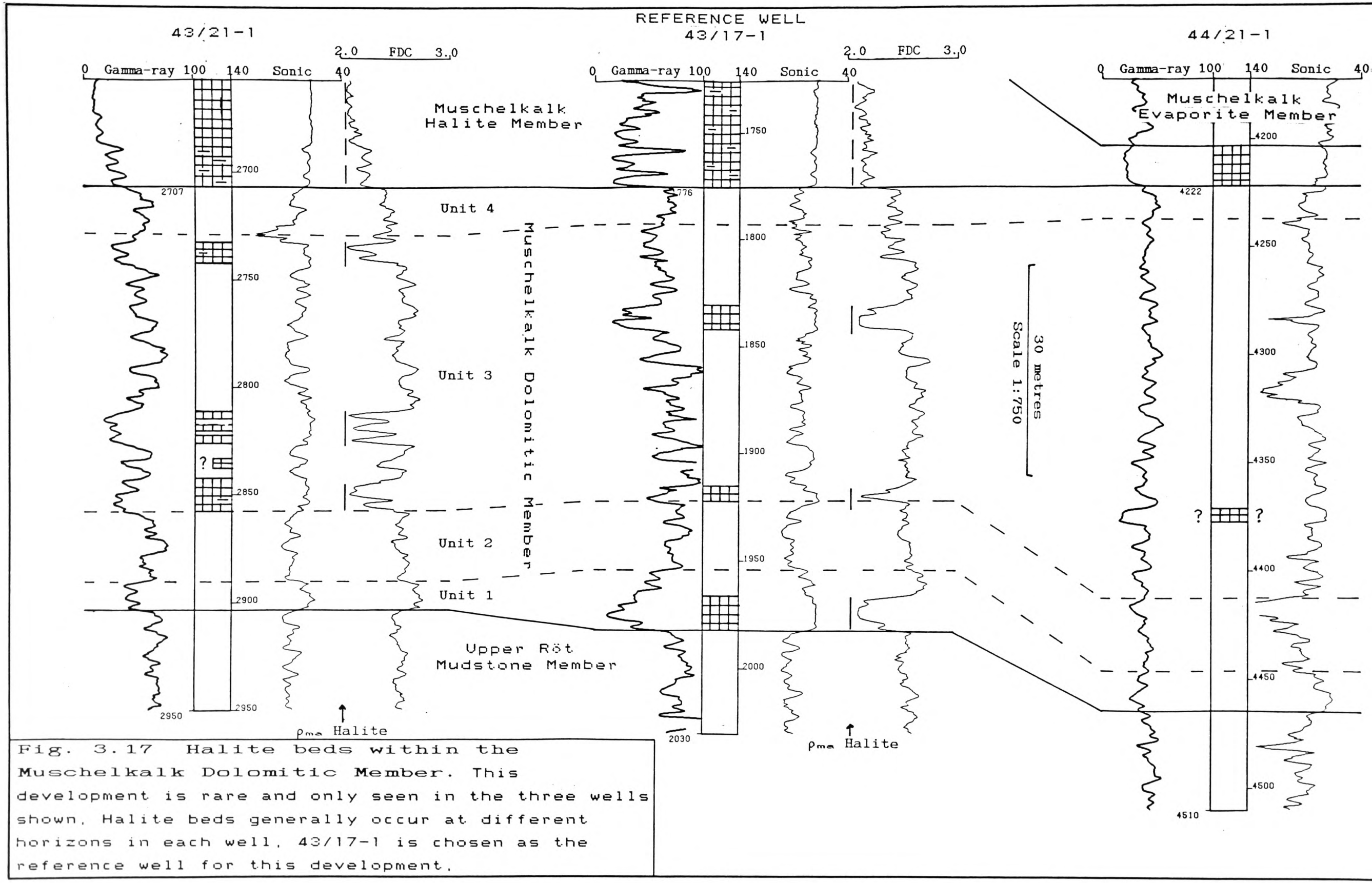


Fig. 3.17 Halite beds within the Muschelkalk Dolomitic Member. This development is rare and only seen in the three wells shown. Halite beds generally occur at different horizons in each well. 43/17-1 is chosen as the reference well for this development.

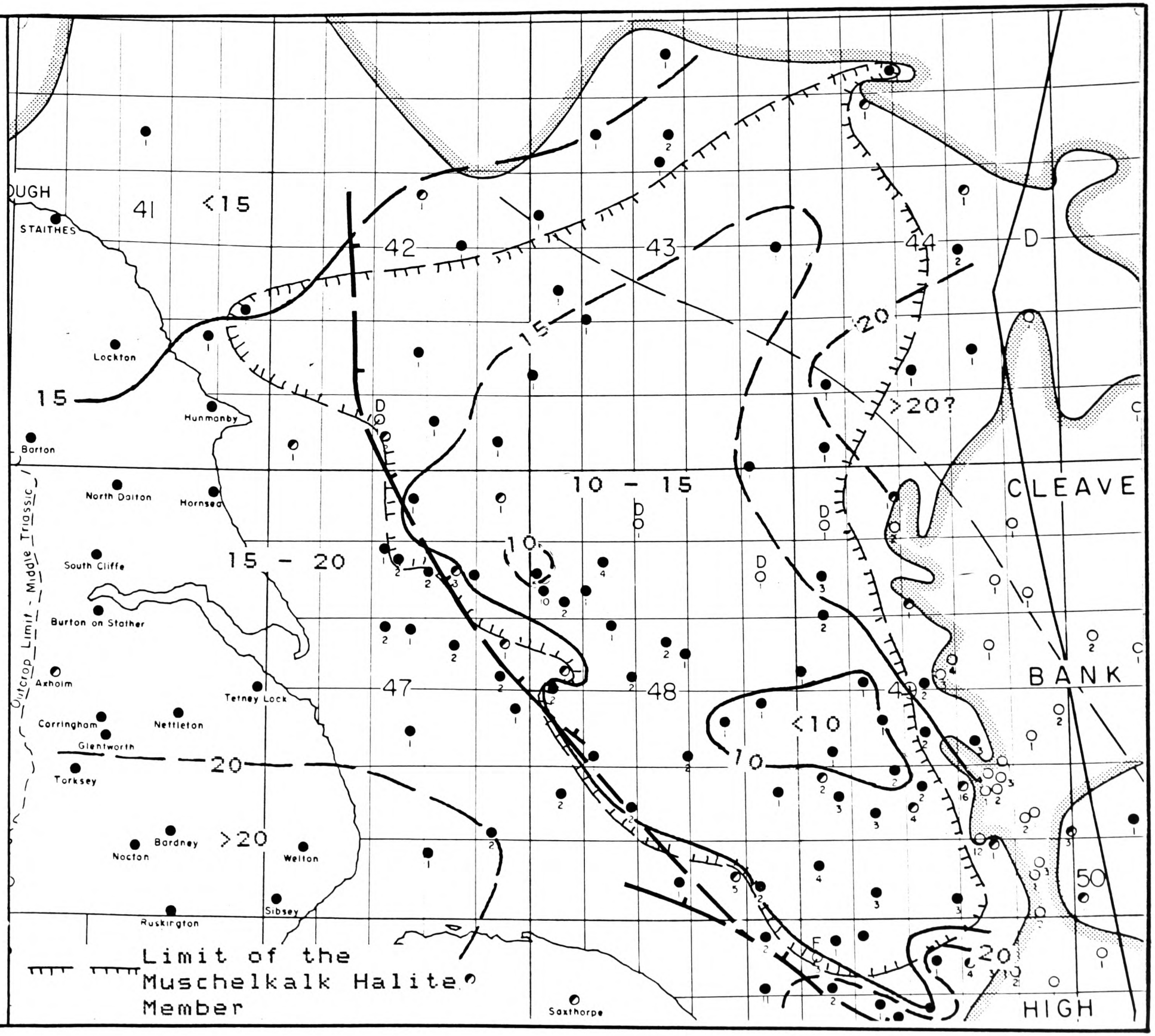
Fig. 3.18
Isopach map of the Muschelkalk Evaporite Member showing the relationship with Muschelkalk Halite Member distribution.

The Member thickens to the margin of the halite basin, and then thins towards the north-west. Towards the south-west, it continues to thicken due to clastic input from the margin.

Thicknesses in individual wells are listed in Appendix A Table 2.

Scale 1:1,500,000

Isopachs in metres



	EAST ENGLAND	UK SECTOR	DUTCH SECTOR	EAST HOLLAND	NORTH GERMANY	DEN-MARK
Lower Keuper		[A] (Ca?)	La-No	[A]	[A]	
Muschelkalk Mudstone		La	La	La	La	La
		[B]			[B]	
Muschelkalk Evaporite		An	An-La		An	An
		[C]		[C]	[C]	
Muschelkalk Dolomitic	An	An	An-La		An	
Upper Röt Mudstone	Sk	Sk	Sk-?An		Sk	
Upper Röt Evaporite	Sk		Sk-?An		Sk	
Intermediate Röt Mudstone	Sk		Sk-?An		Sk	
Main Röt Evaporite	Sk		Sk-?An	Sk	Sk	
Lower Röt Mudstone						
Solling Mudstone					Sk	
REFERENCES	3,7,8	2,3	1	2,3	2,3,6	4,5

Index:

1	NAM/RGD (1980)	No	Norian
2	Brennand (1975)	Ca	Carnian
3	Geiger and Hopping (1968)	La	Ladinian
4	Jacobsen (1982)	An	Anisian
5	Bertelsen (1980)	Sk	Skythian
6	Gall *et al* (1977)		
7	Warrington (1974)	[A]	markers
8	Woods (1973)	[B]	Geiger &
		[C]	Hopping

FIG. 3.19 Lithostratigraphy v. Biostratigraphy of the Dowsing Dolomitic Formation and equivalents across the study area.

OLD TERMINOLOGY		ACCEPTED TERMINOLOGY (Warrington *et al* 1980)	
RHAETIC		PENARTH GROUP	
KEUPER MARL GROUP	KEUPER MARL	PARVA FORMATION	UPPER MERCIA MUDSTONE *s.s.*
		TRENT FORMATION	
		Hollygate Skerry EDWALTON FORMATION Cotgrave Skerry	
		HARLEQUIN FORMATION	
		Plains Skerry CARLTON FORMATION	
		RADCLIFFE FORMATION	LOWER MERCIA MUDSTONE GROUP *s.l.*
KEUPER SANDSTONE	WATERSTONES FORMATION	COLWICK FORMATION	
	KEUPER BASEMENT BEDS GREEN BEDS	WOODTHORPE FORMATION RETFORD FORMATION	
BUNTER SANDSTONE		SHERWOOD SANDSTONE GROUP	

FIG. 4.1

LITHOSTRATIGRAPHIC NOMENCLATURE OF THE MERCIA MUDSTONE GROUP AROUND NOTTINGHAM, EASTERN ENGLAND

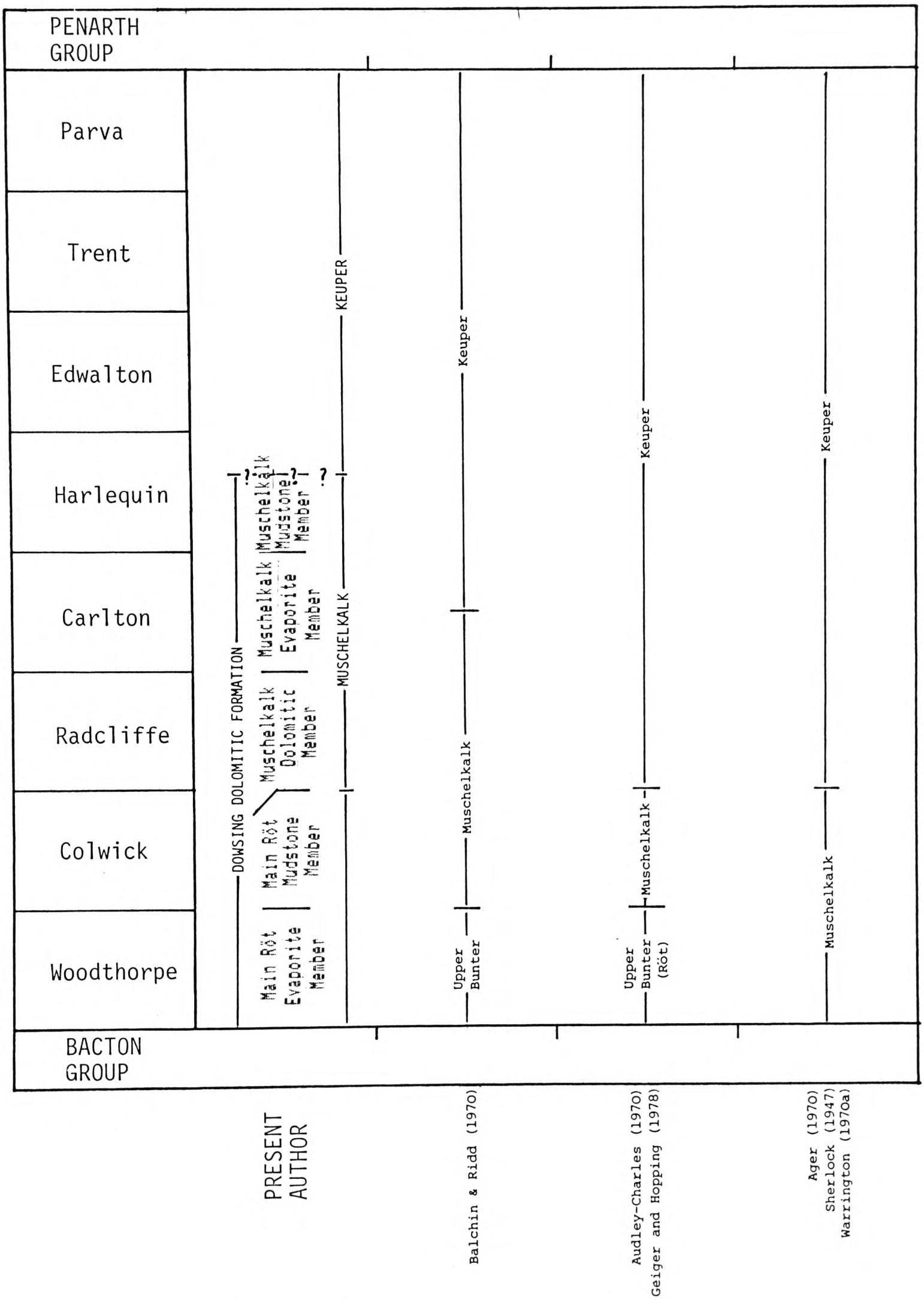


FIG. 4.2

VARIOUS CORRELATIONS BETWEEN THE NOTTINGHAM AND GERMANIC LITHOSTRATIGRAPHIES

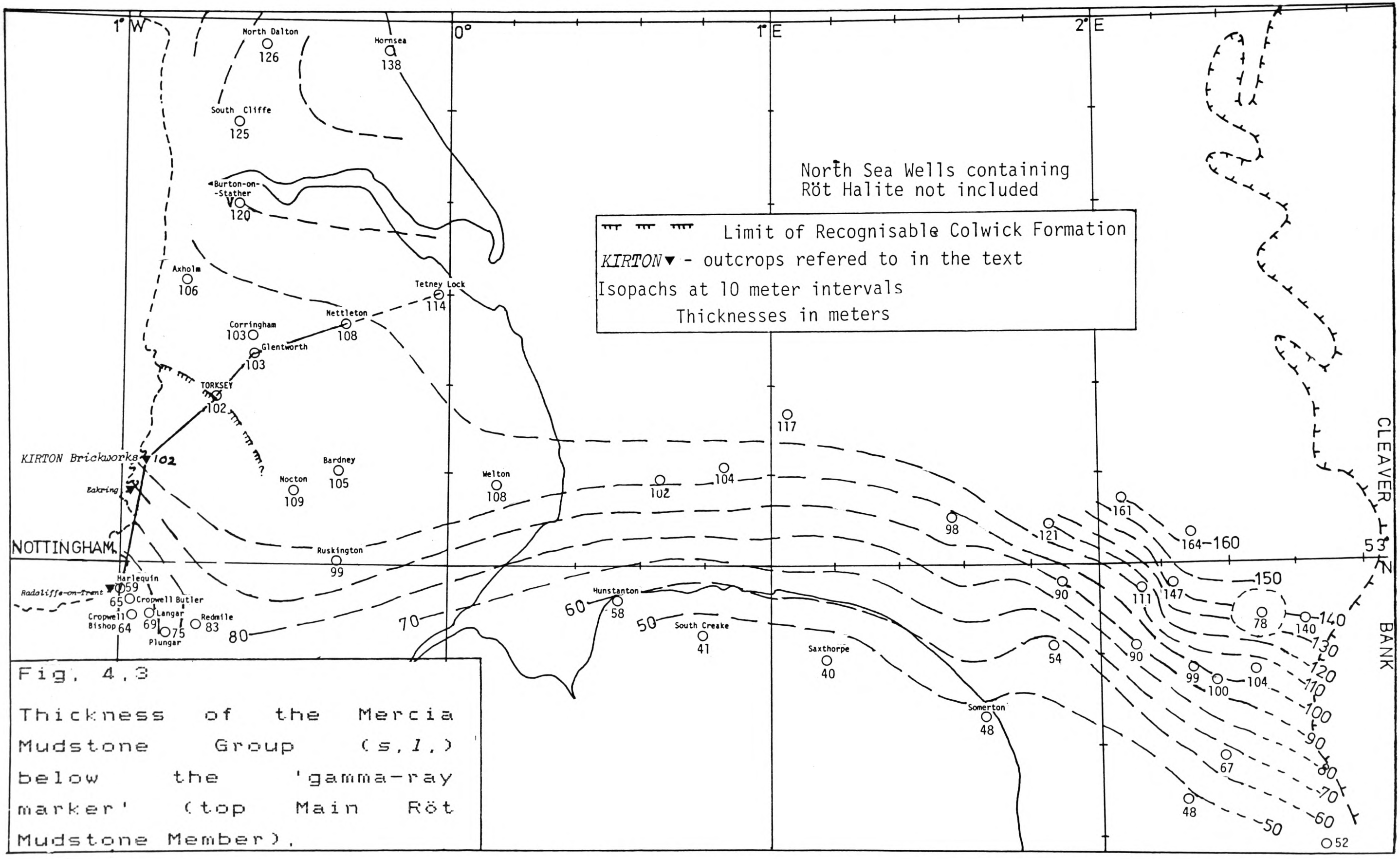


Fig. 4.3

Thickness of the Mercia Mudstone Group (s.l.) below the 'gamma-ray marker' (top Main Röt Mudstone Member).

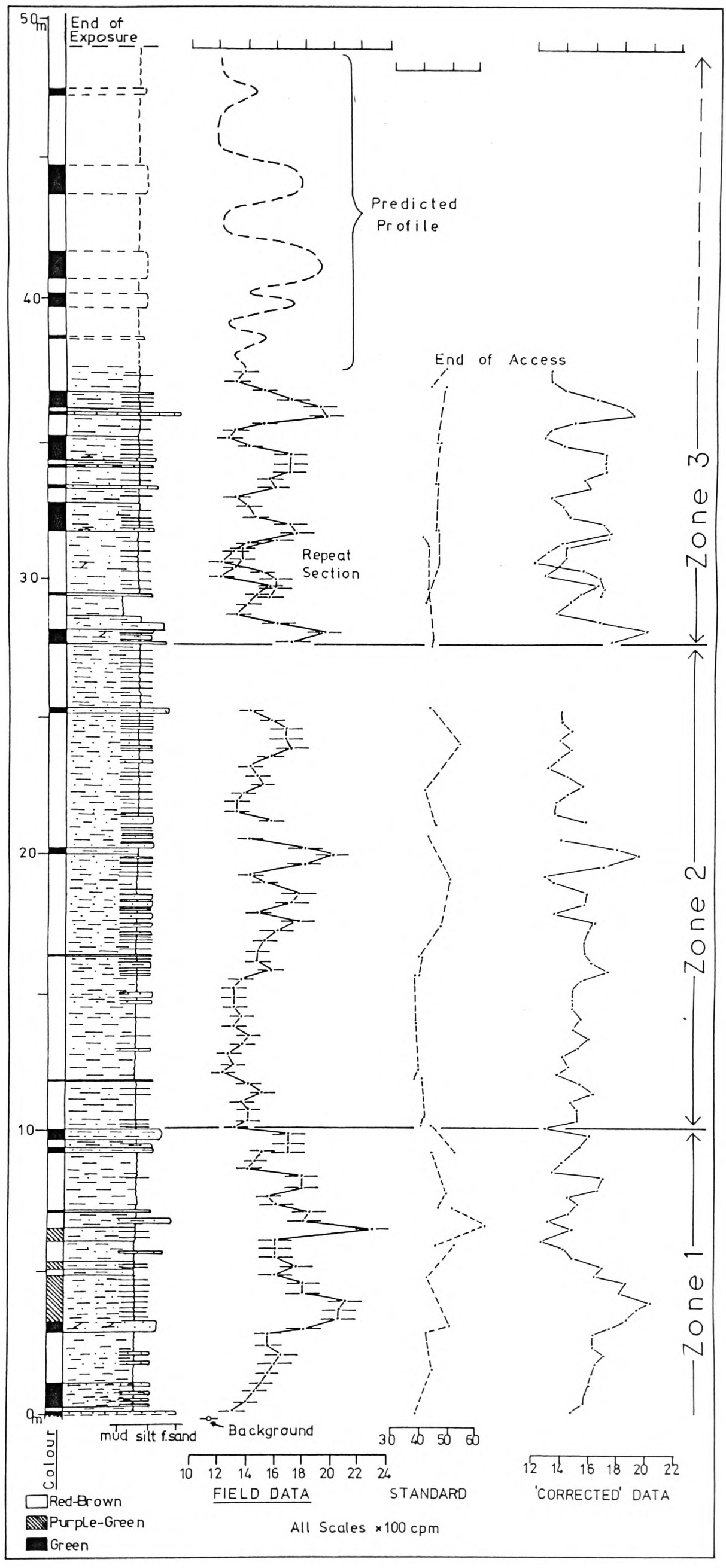
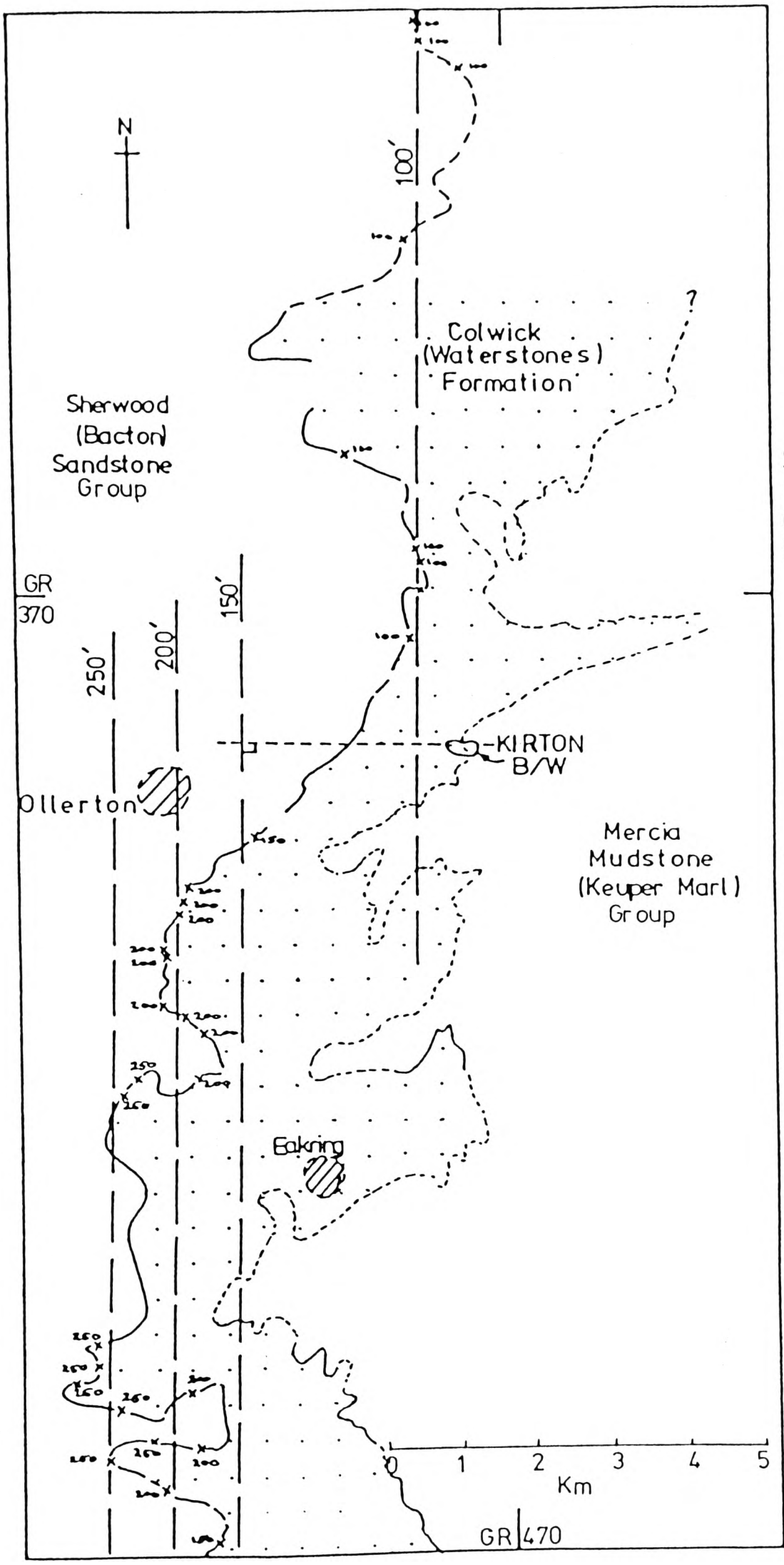


Fig. 4.4 KIRTON BRICKWORKS

Lithology and Gamma-ray profiles



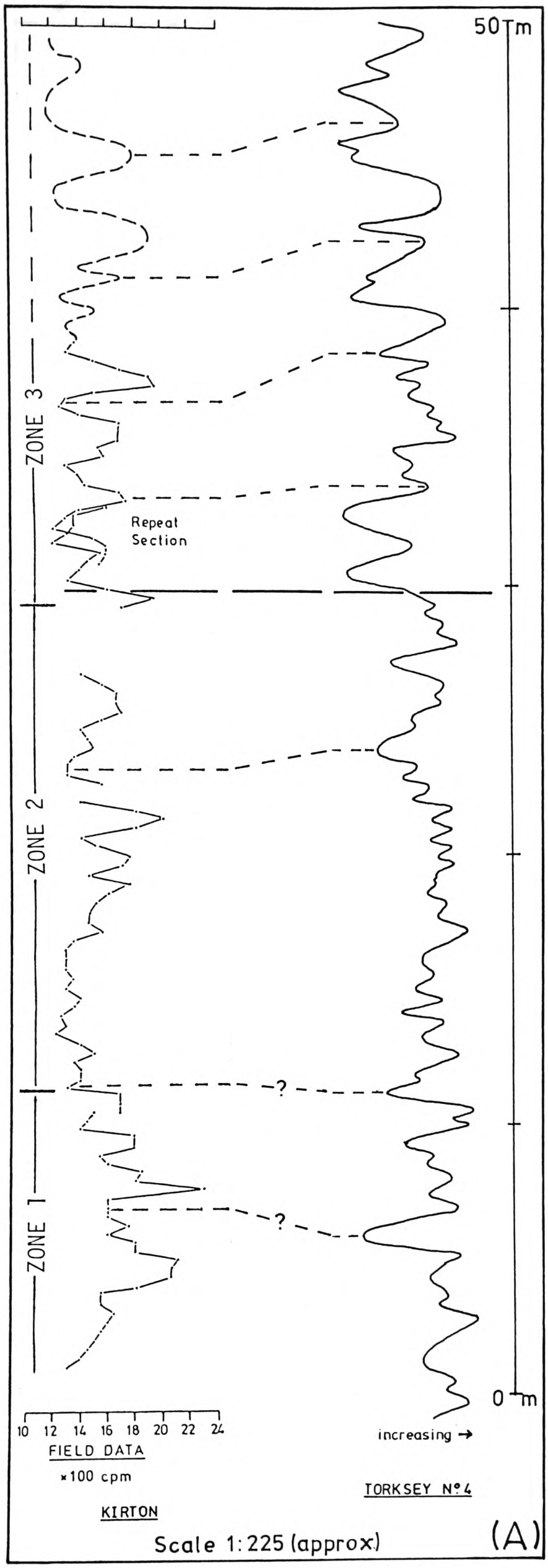
Structural Contours on the top of the Sherwood Sandstone Group at 50 feet intervals. Based on elevations shown.

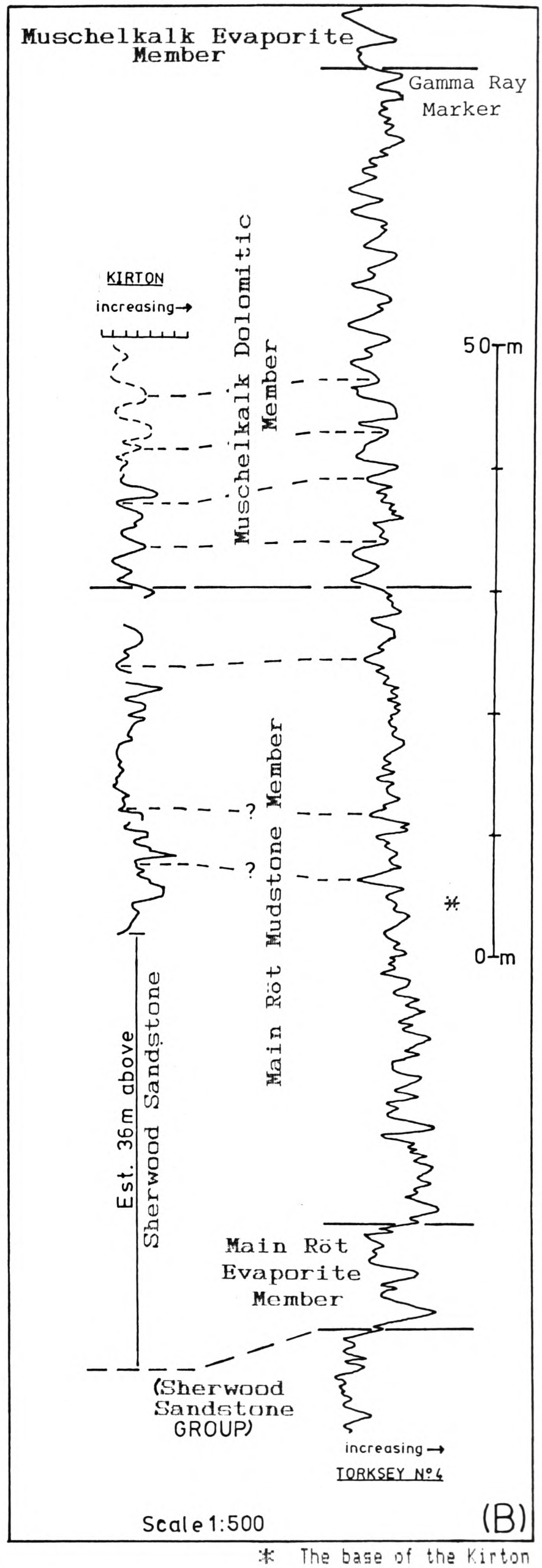
Dip of top of Sherwood Sandstone Group (near Kirton = 0.37°

Thickness of Mercia Mudstone Group below Kirton succession = 36m.

Fig. 4.5

THICKNESS OF THE MERCIA MUDSTONE GROUP BELOW THE BASE OF THE KIRTON SUCCESSION





* The base of the Kirton profile as estimated from fig. 4.5

Fig. 4.6

Gamma-ray correlation between Kirton Brickworks and Torksey-4 well.

(A) Detailed correlation
(B) Estimated height above the Sherwood Sandstone Group

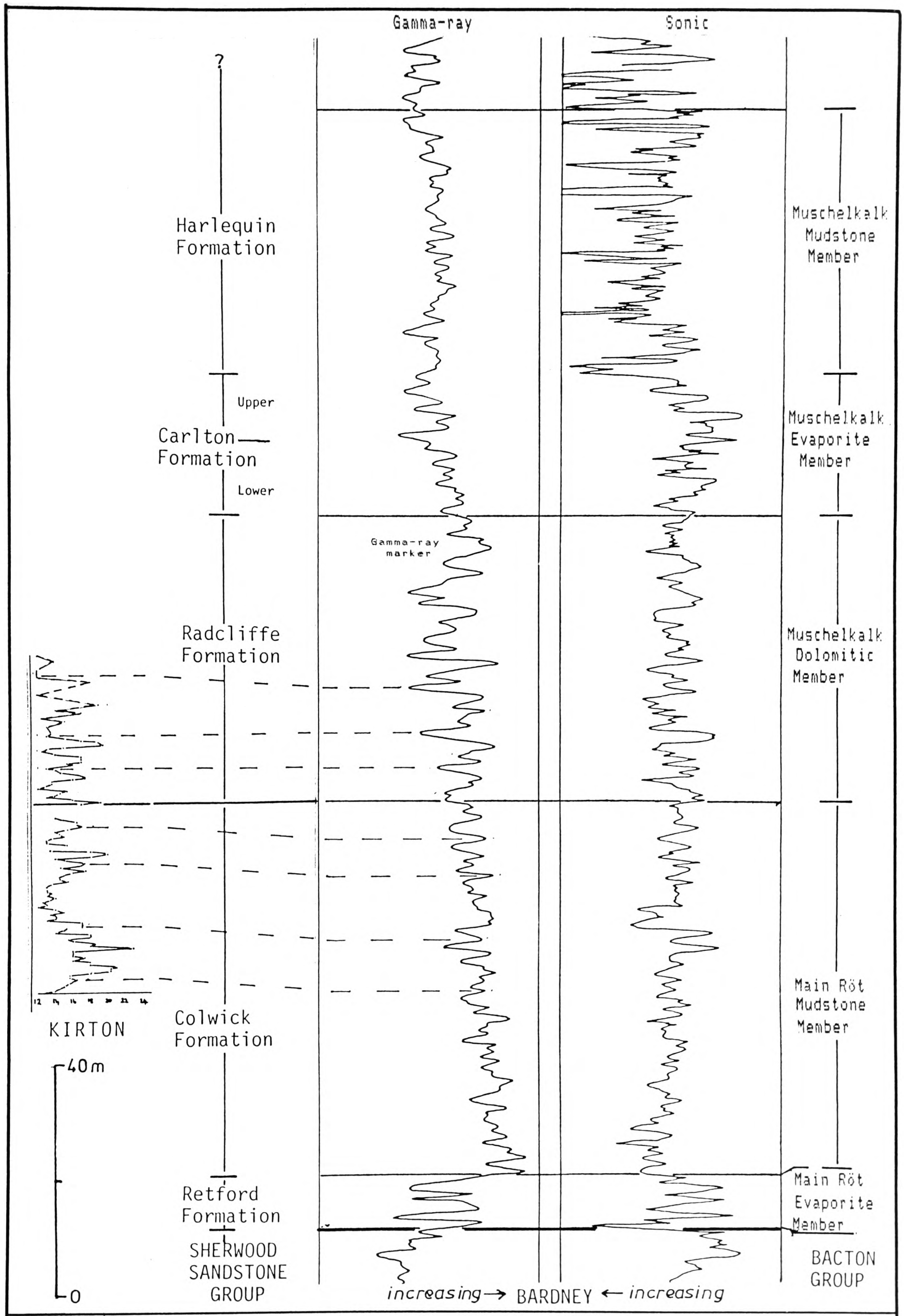


Fig. 4.7
Recognition of the Nottingham (surface) litho-stratigraphy in the Bardney well, and comparison with the subsurface lithostratigraphy.

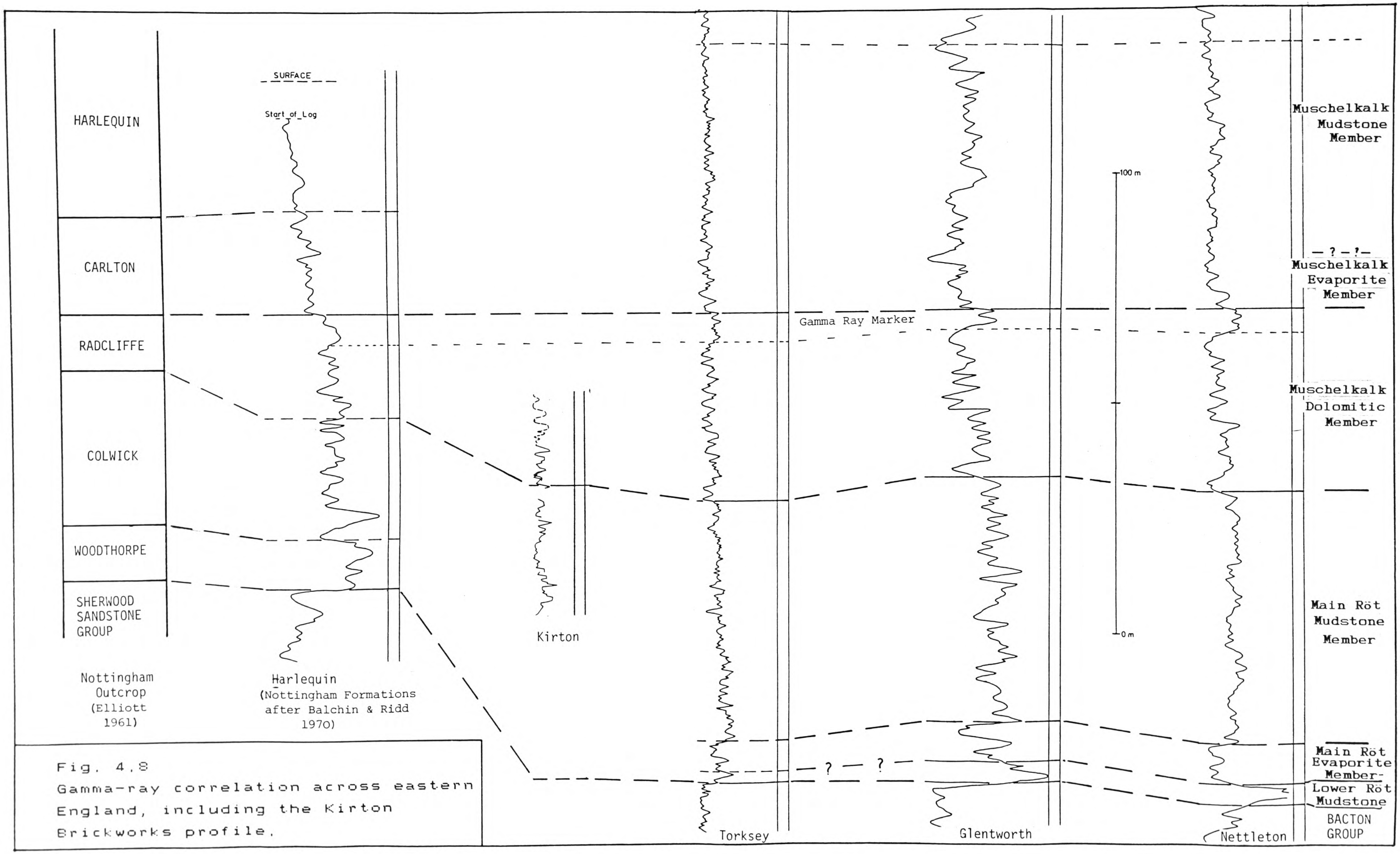


Fig. 4.8
Gamma-ray correlation across eastern England, including the Kirton Brickworks profile.

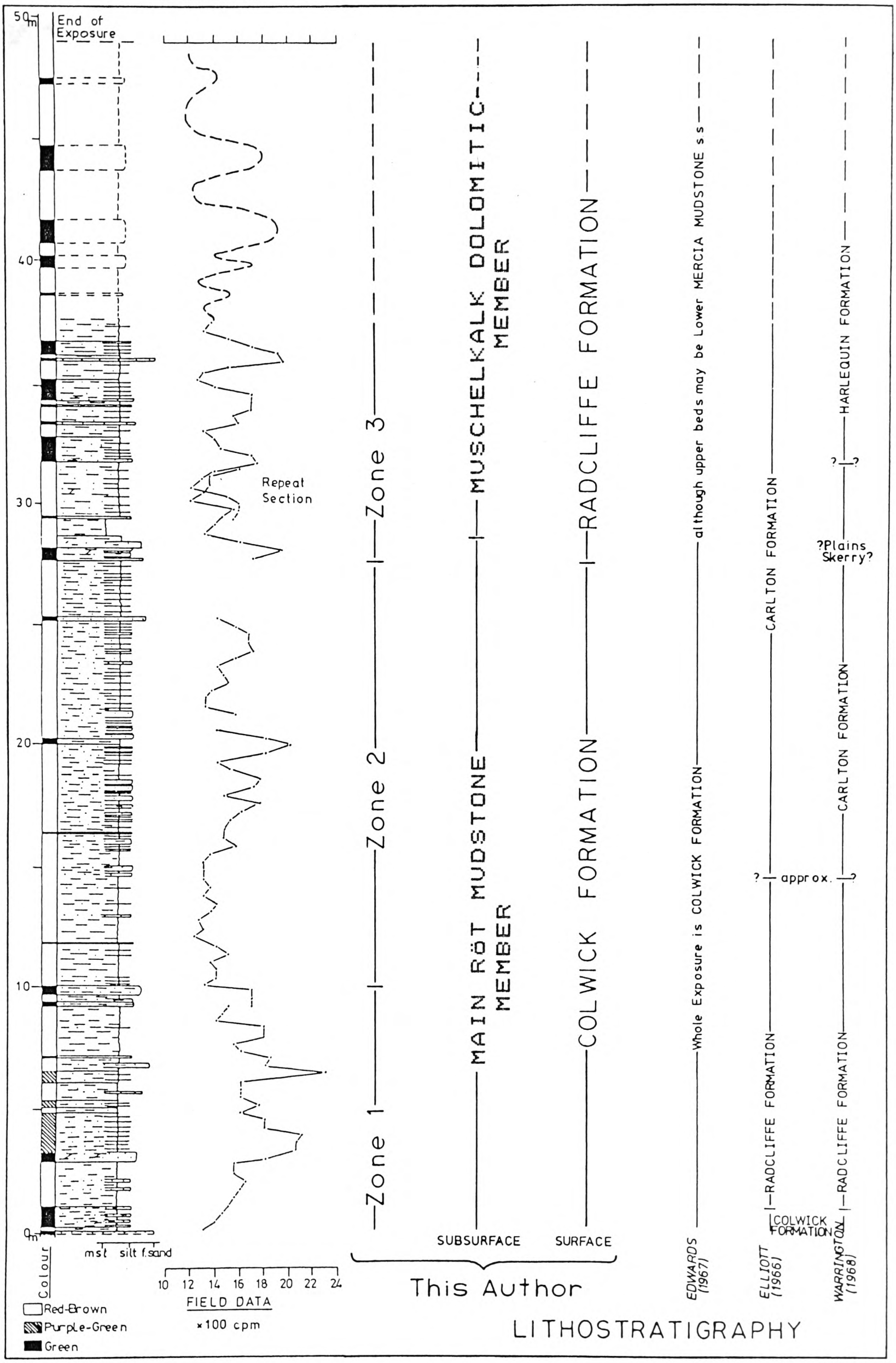
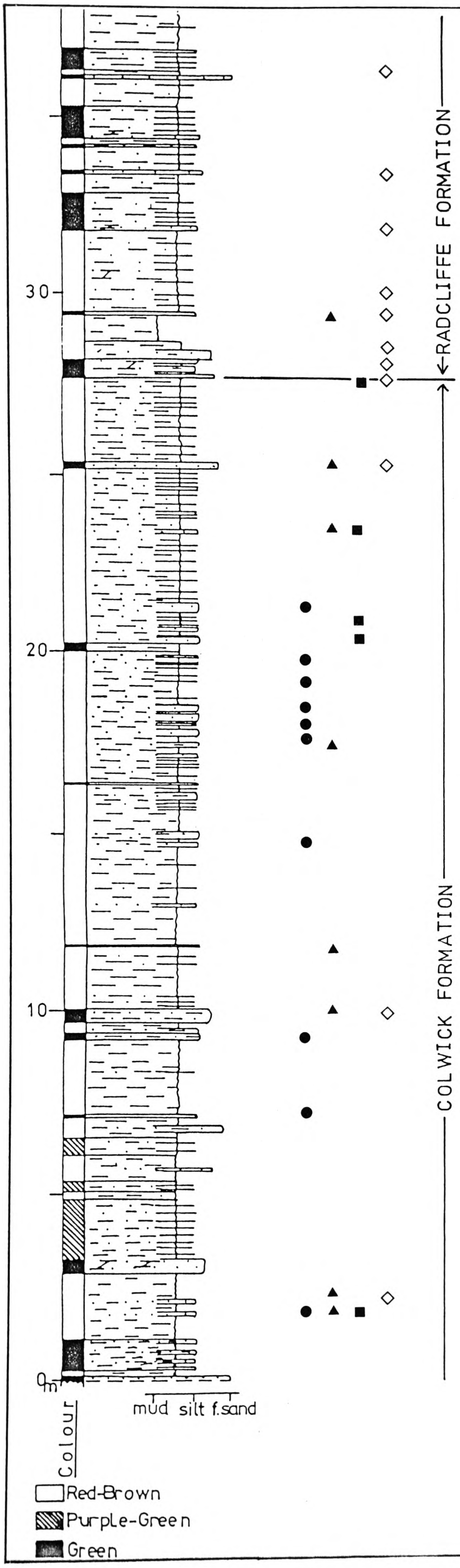
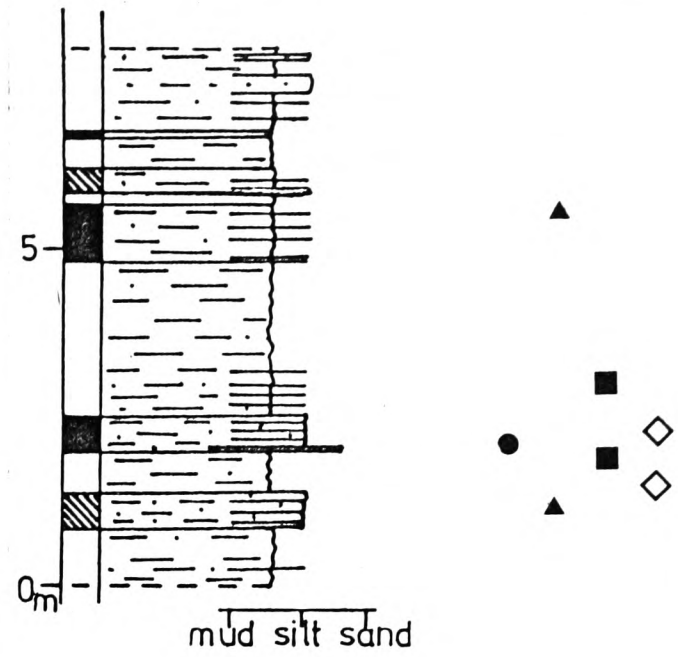


Fig. 4.9

LITHOSTRATIGRAPHY OF THE KIRTON BRICKWORKS





Colour code as opposite*

*However, green and purple-green horizons show slightly reddish hues and contain interbedded red mudstones at this locality

Radcliffe-on-Trent
River Cliff

Type Locality : RADCLIFFE FORMATION

(INSET)

- ● Cross-lamination
- ▲ Ripple marks
- ■ Basal scours/loading
- ◇ Halite pseudomorphs

Kirton
Brickworks

Fig. 4.10

CURRENT DEPOSITED AND EVAPORITIC SEDIMENTARY STRUCTURES, KIRTON BRICKWORKS

(Inset: Radcliffe Formation, Type Locality)

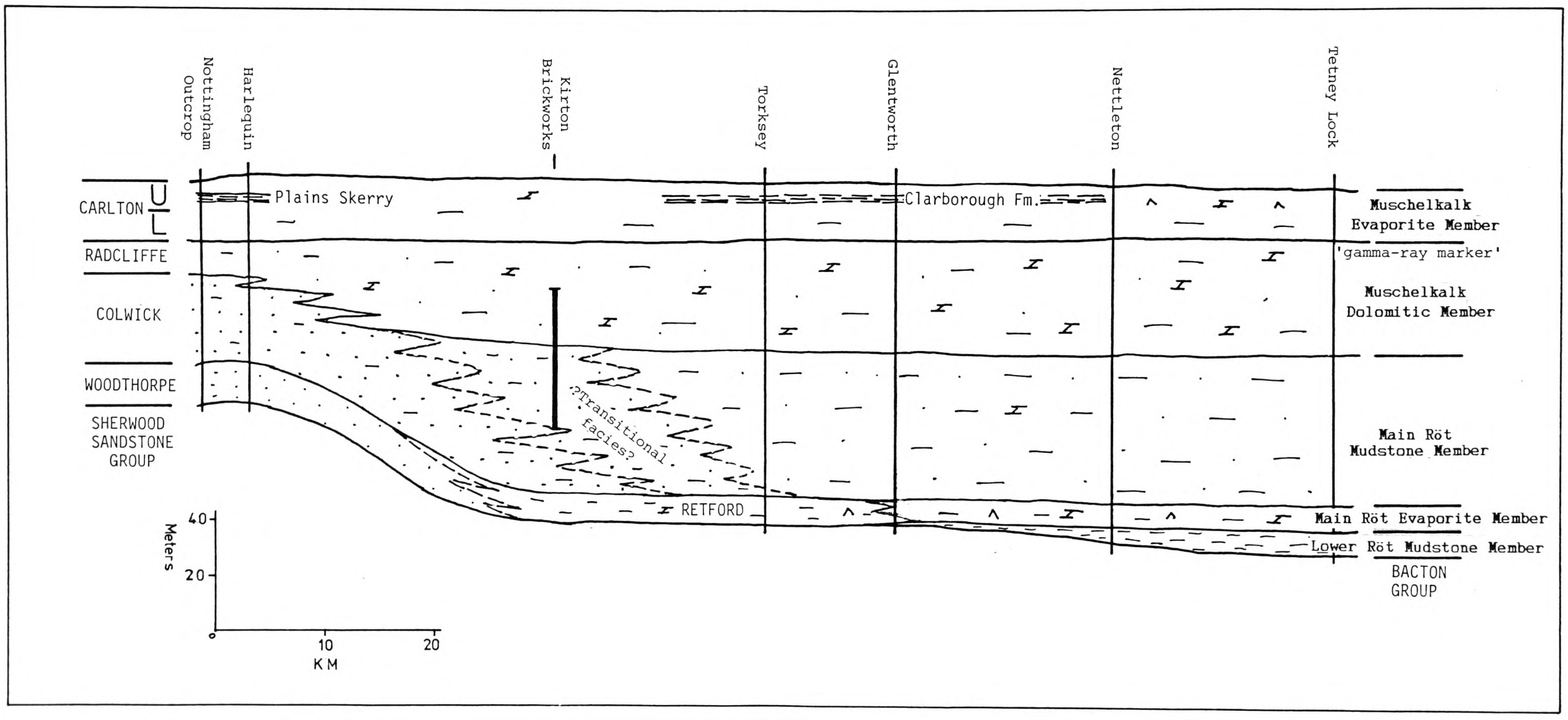


Fig. 4.11

Relationship between the Nottingham and North Sea lithostratigraphies.

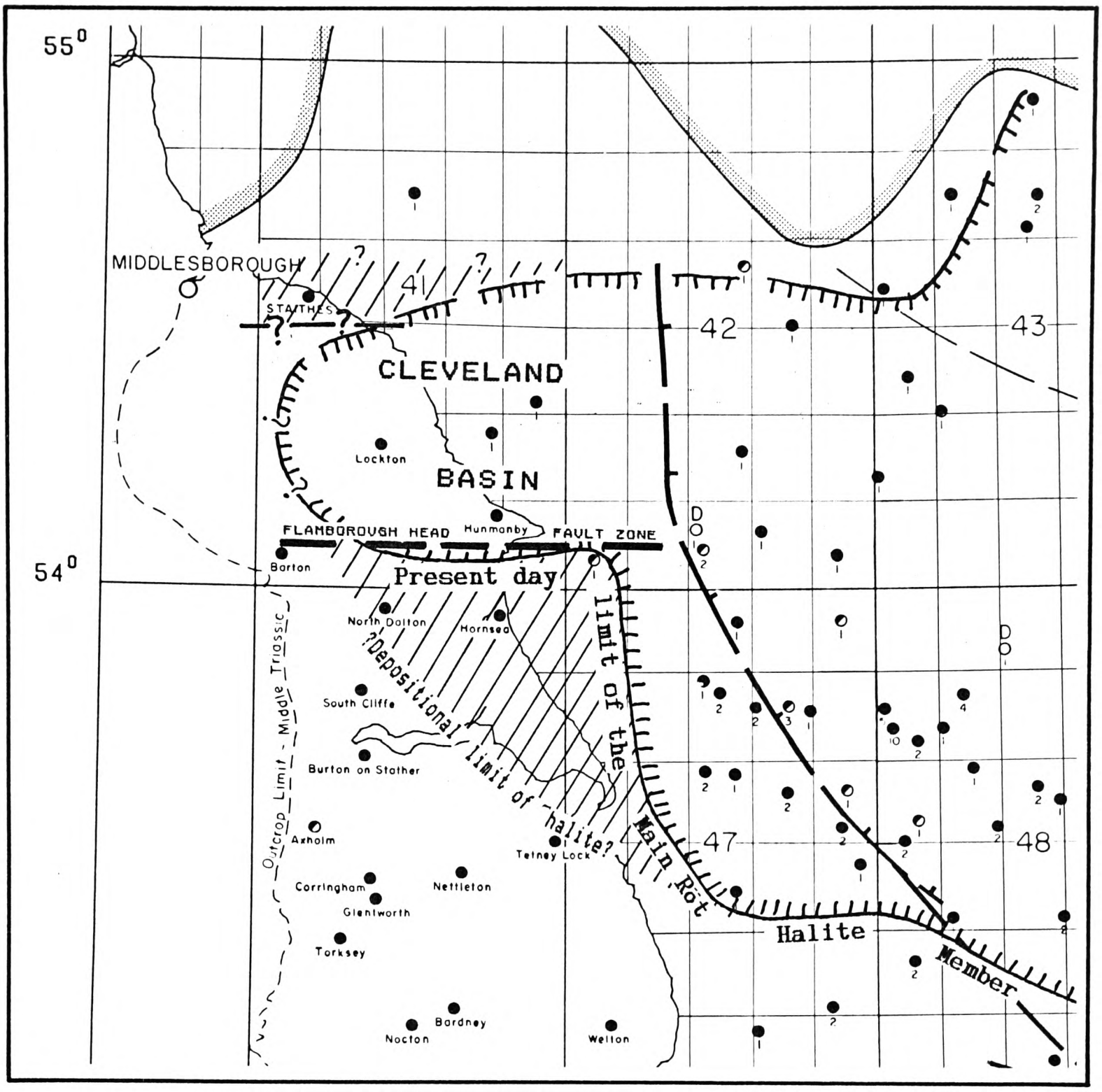
	Nottingham Outcrop (Elliott 1961)	Harlequin Well (Balchin & Ridd 1970)	KIRTON Brickworks	Torksey Well	Bardney Well	Tetney Lock Well
PENARTH GROUP						
Parva	146	not present	not present	151	137	146
Trent						
Edwalton						
Harlequin						
Carlton	21	25		20?	21	17?
Radcliffe	12	21	38	41	42	42
Colwick/ equivalent	34	19	64	52	55	55
Woodthorpe/ Retford	12	18		9	9	16
BACTON GROUP						

← MARGIN → ← BASIN →

Kirton:
-Thicknesses as explained in text

Fig. 4.12

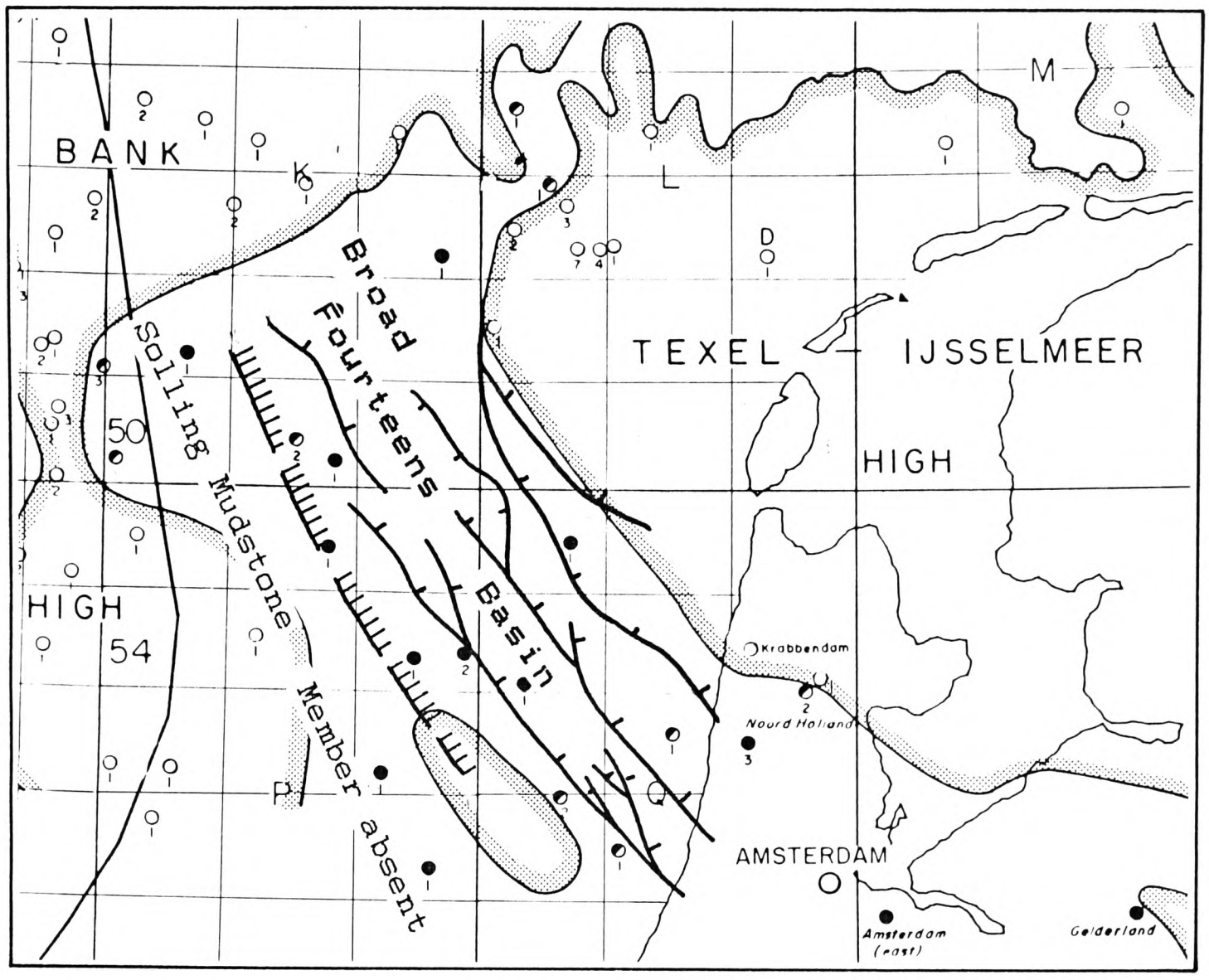
THICKNESS OF THE NOTTINGHAM FORMATIONS AND THEIR LATERAL EQUIVALENTS ACROSS EASTERN ENGLAND



/// Halite removed?

Fig. 5.1

Postulated depositional margin of the Main Röt Halite Member basin on the East Midlands Shelf. Post-Jurassic dissolution resulted in halite being preserved only in the deeper buried Cleveland Basin. Based on the distribution of individual halite cycles (encl. Map 11).



Margin Solling Mudstone Member

Fig. 5.2

The depositional margin of the Solling Mudstone Member in the Southern Dutch Sector lies close to and parallels the boundary faults of the Broad Fourteens Basin.

Solling Mudstone Member margin: from encl. Map 2. Broad Fourteens Basin faults from: 'Sub-crop map late Cimmerian unconformity' published by Geologic Ltd.

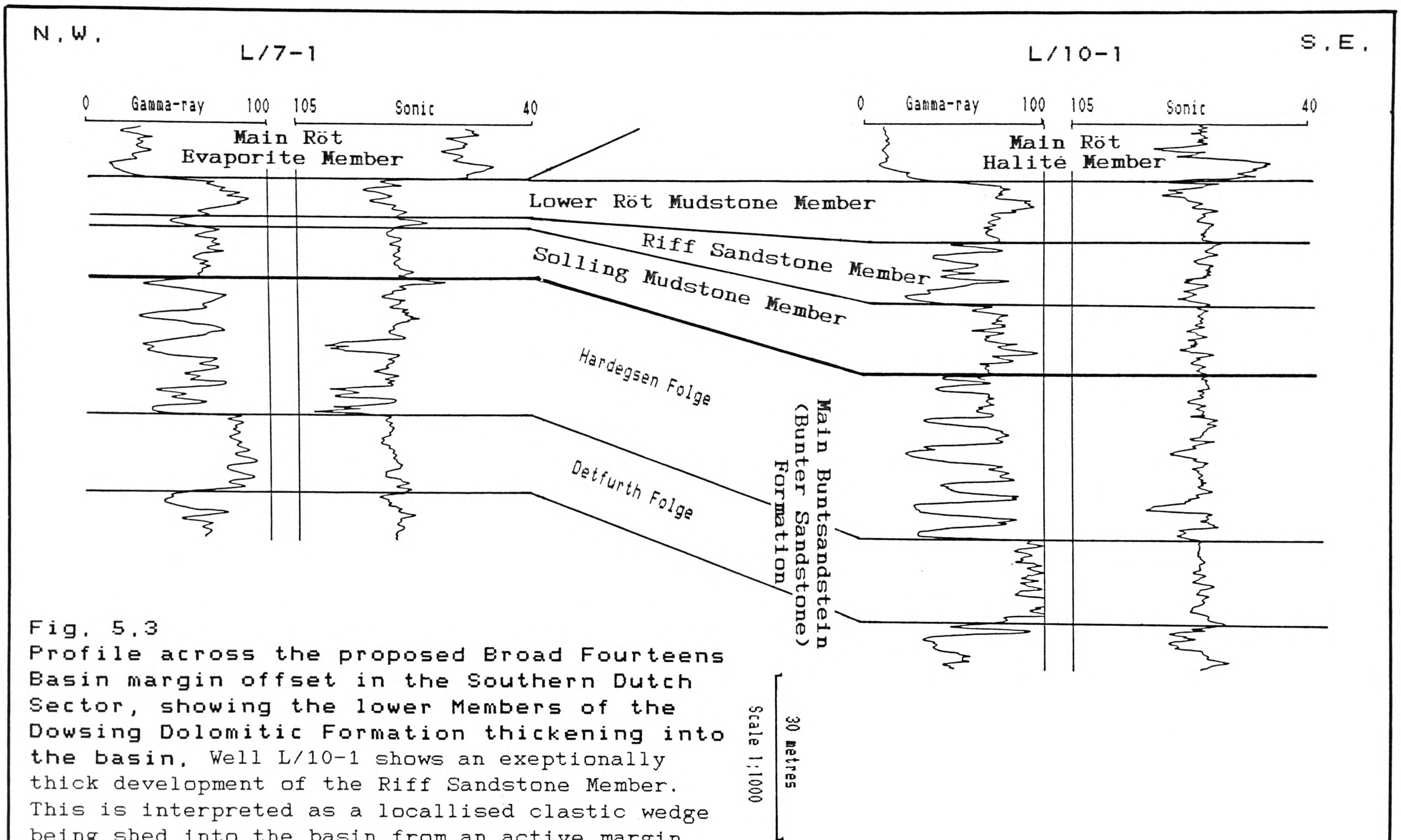


Fig. 5.3
Profile across the proposed Broad Fourteens Basin margin offset in the Southern Dutch Sector, showing the lower Members of the Dowsing Dolomitic Formation thickening into the basin. Well L/10-1 shows an exeptionally thick development of the Riff Sandstone Member. This is interpreted as a locallised clastic wedge being shed into the basin from an active margin.

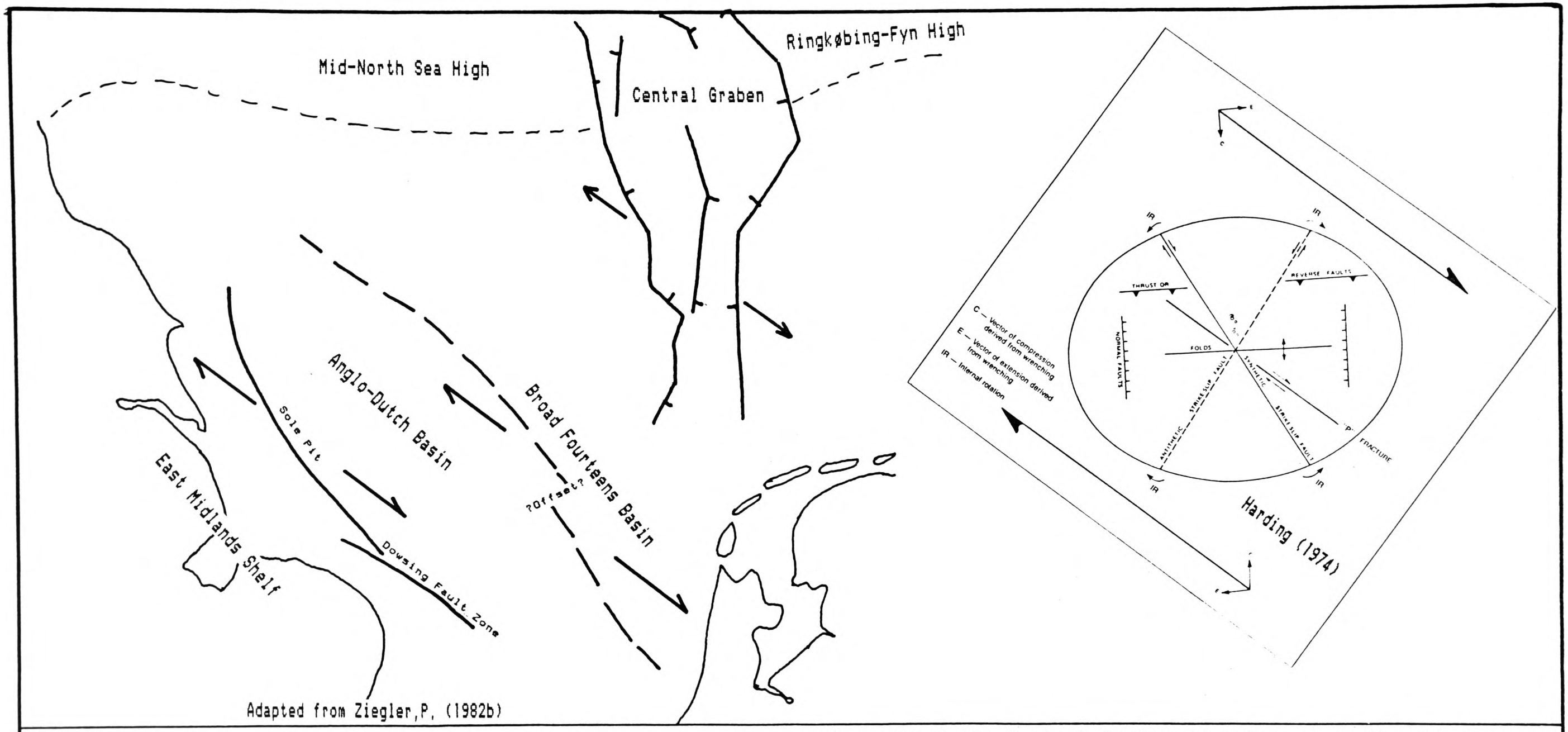


Fig. 5.4
Model to explain the major structural elements active in the Southern North Sea area during Dowsing Dolomitic Formation deposition.

Opening of the Central Graben is taken up in the Southern North Sea by dextral wrenching along the Dowsing Fault Zone, the Broad Fourteens Basin margin and (presumably) other north-west/south-east trending faults. Rapid subsidence on the north-eastern (downthrown) side of these faults (Sole Pit Trough, Broad Fourteens Basin) indicates a transtensional regime. Structures agree with those predicted by the dextral wrench ellipse of Harding (1974). Based on observed thicknesses, plus Glennie (1986) and Ziegler,P. (1982b).

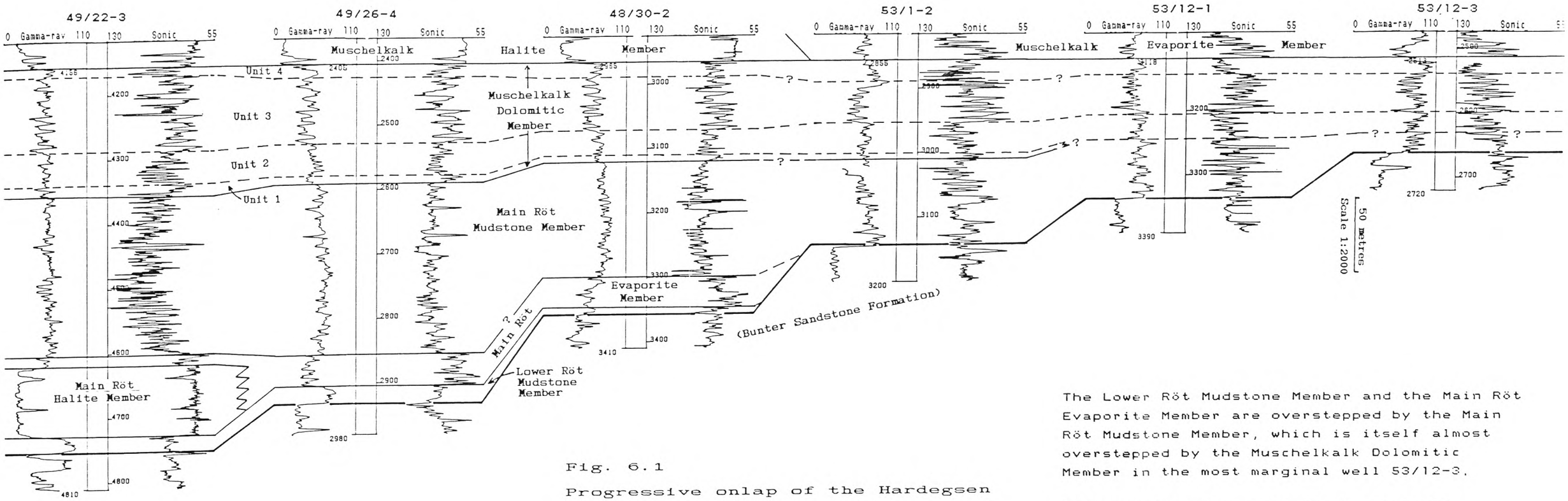


Fig. 6.1
Progressive onlap of the Hardegsen unconformity surface towards the southern margin of the Germanic Basin in the U.K. Southern North Sea.

The Lower Röt Mudstone Member and the Main Röt Evaporite Member are overstepped by the Main Röt Mudstone Member, which is itself almost overstepped by the Muschelkalk Dolomitic Member in the most marginal well 53/12-3.

Transgressive Unit 1 of the Muschelkalk Dolomitic Member does not reach the southern part of Quadrant 53, although transgressive Unit 3 does extend into this area.

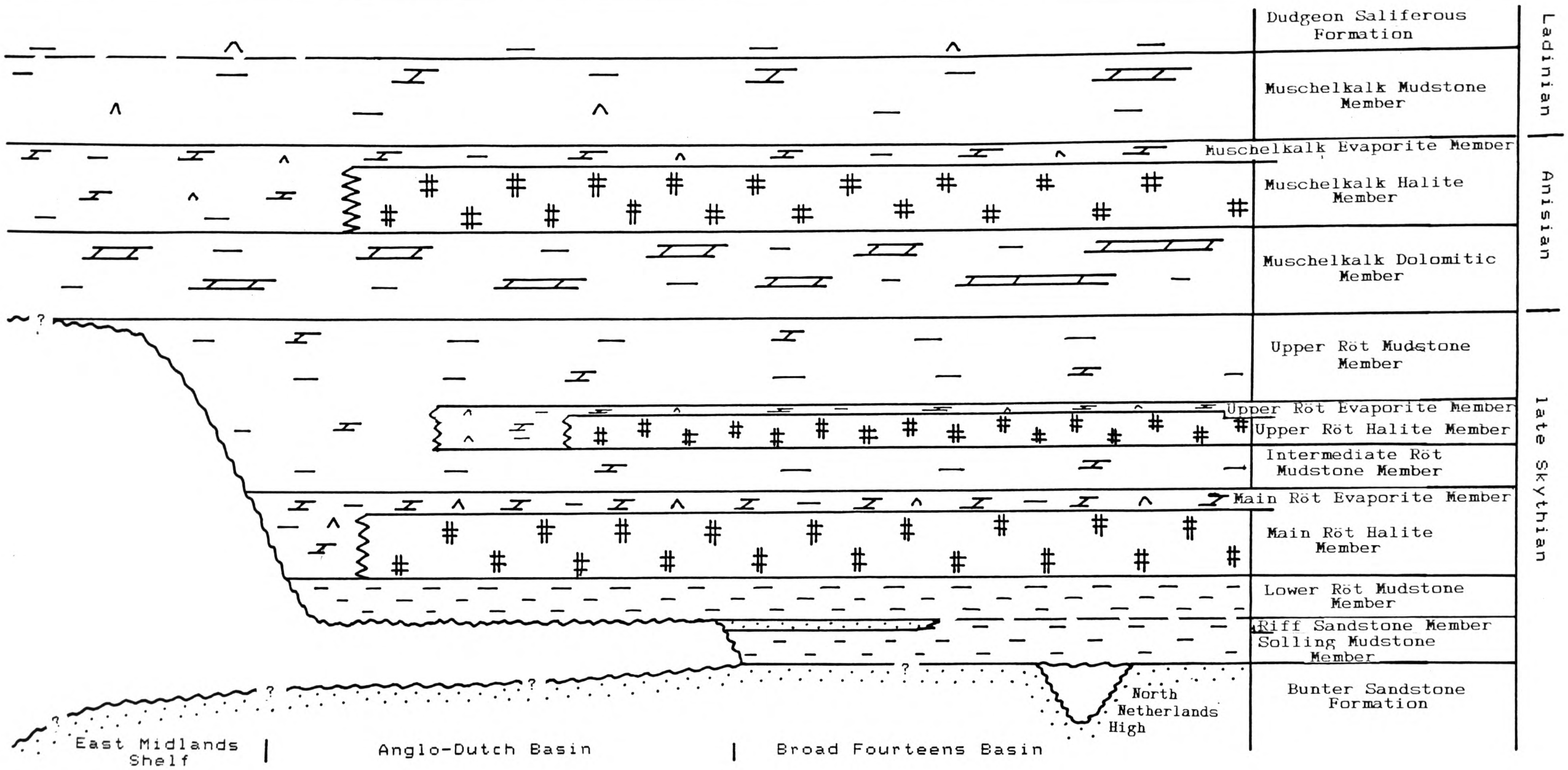
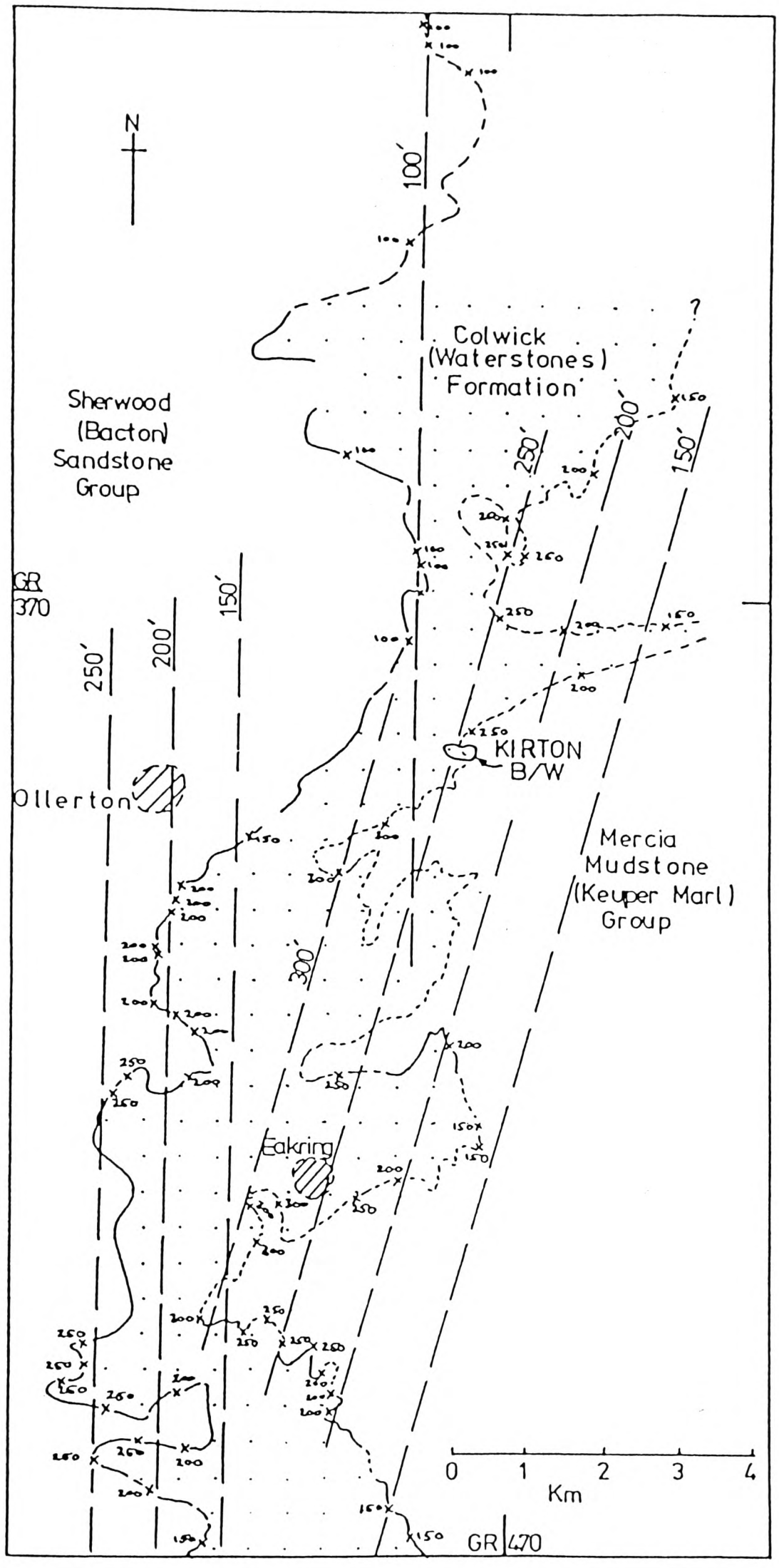


Fig. 6.2

The Hardegsen Unconformity in the Southern North Sea area. Schematic cross-section from the Broad Fourteens Basin to the southern margin of the Germanic Basin.



Strike lines on top of Sherwood Sandstone Group and top of Colwick Formation at 50 feet intervals. Based on elevations shown.

Dip on top of Sherwood Sandstone Group
= 1.5° - 0.4° towards 091°

Dip on top of Colwick Formation = 0.9° towards 106°

Fig. 6.3
The angular Hardegsen unconformity on the East Midlands Shelf in the area around Kirton Brickworks, north of Nottingham. Based on the B.G.S. Map Sheet 113.

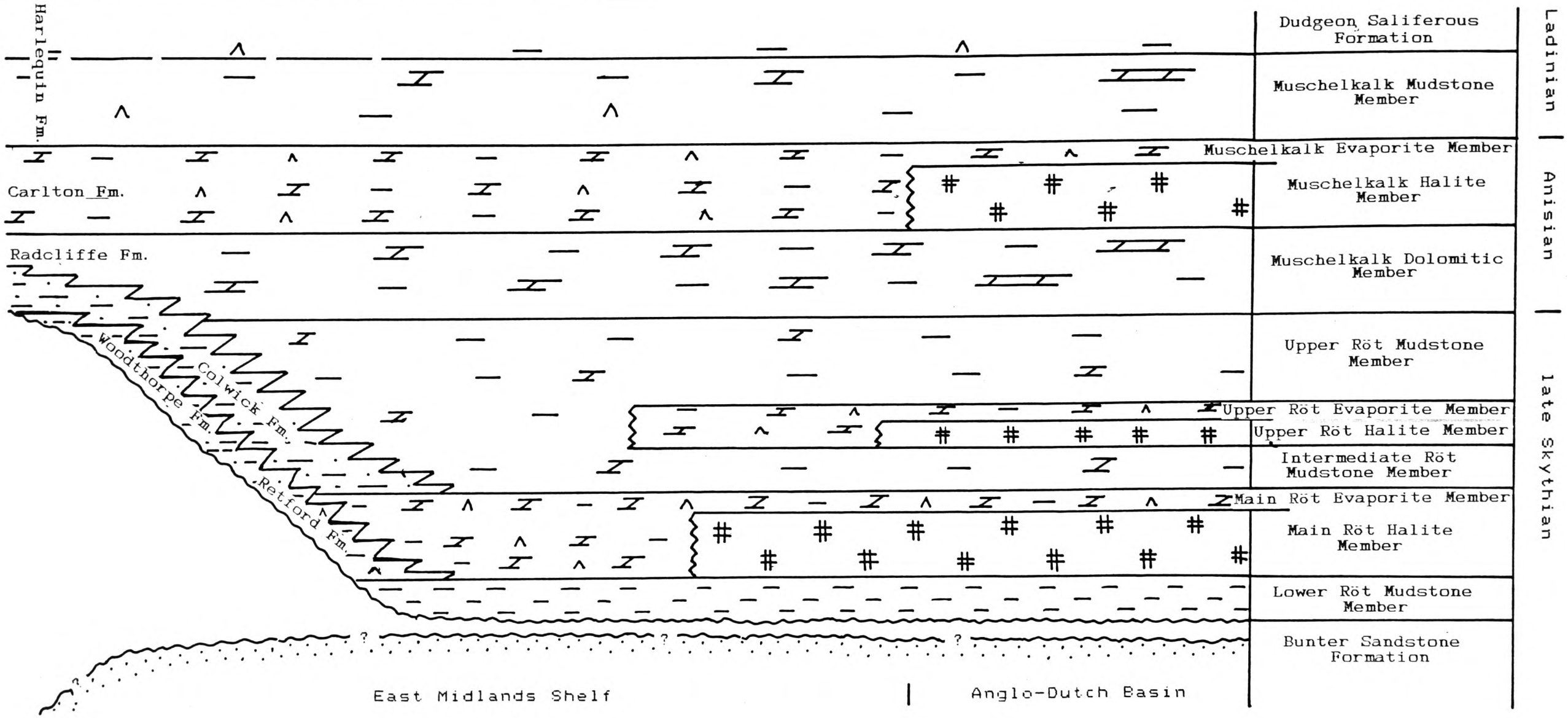
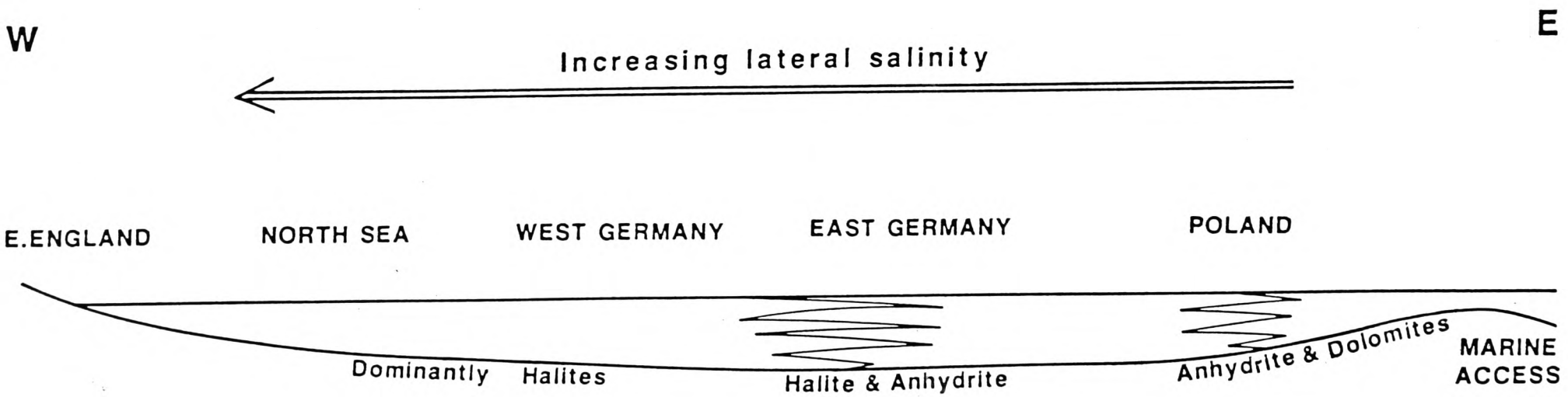


Fig. 6.4

The Hardegsen Unconformity across the East Midlands Shelf. Schematic cross-section from the Anglo-Dutch Basin to the southern margin of the Germanic Basin around Nottingham.

LATERAL SALINITY GRADIENT ACROSS MAIN RÖT HALITE BASIN



References: --- This study --- DOCKTER et al (1980) TOKARSKI (1965)

Fig. 6.5

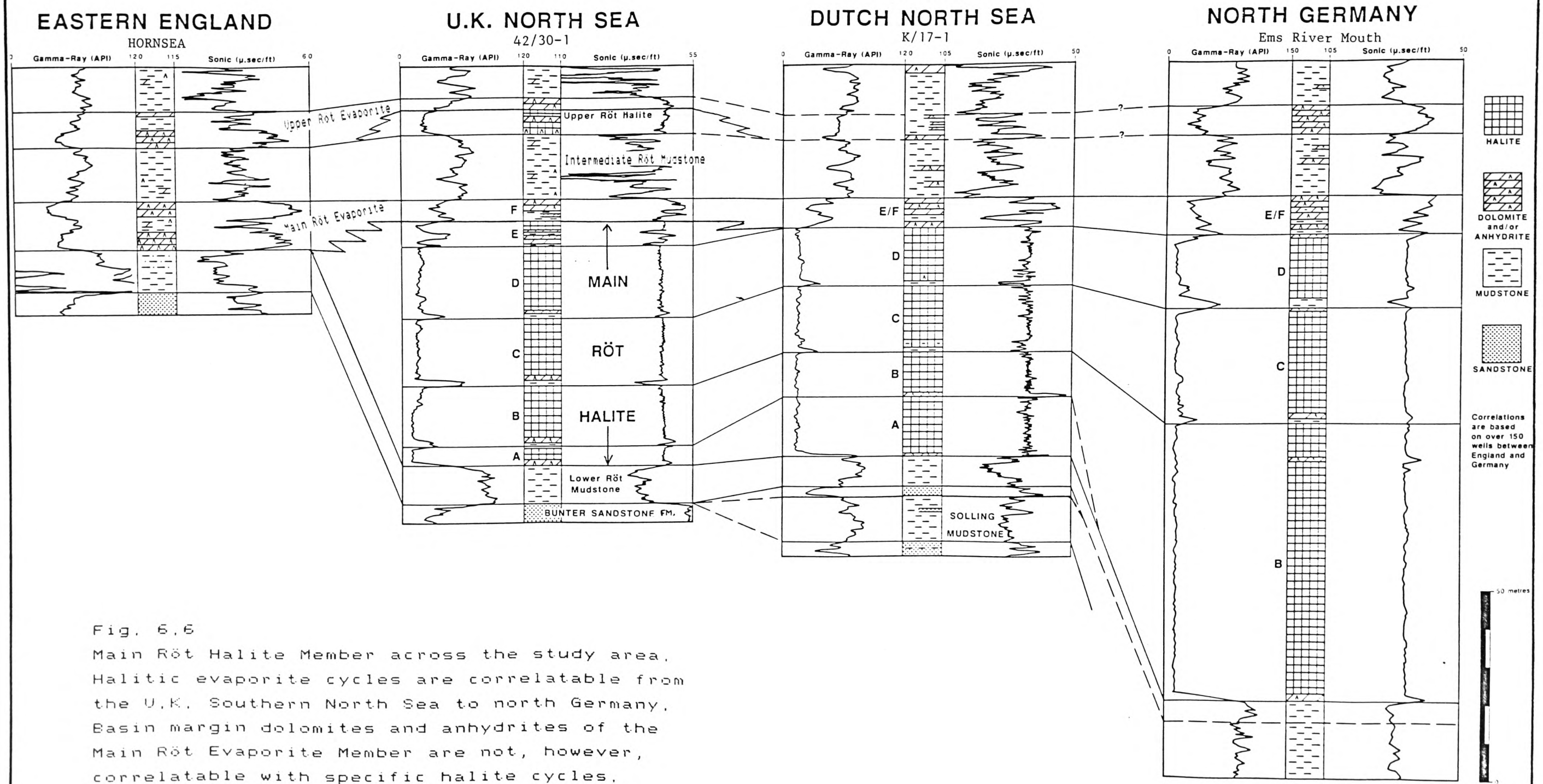


Fig. 6.6
Main Röt Halite Member across the study area. Halitic evaporite cycles are correlatable from the U.K. Southern North Sea to north Germany. Basin margin dolomites and anhydrites of the Main Röt Evaporite Member are not, however, correlatable with specific halite cycles.

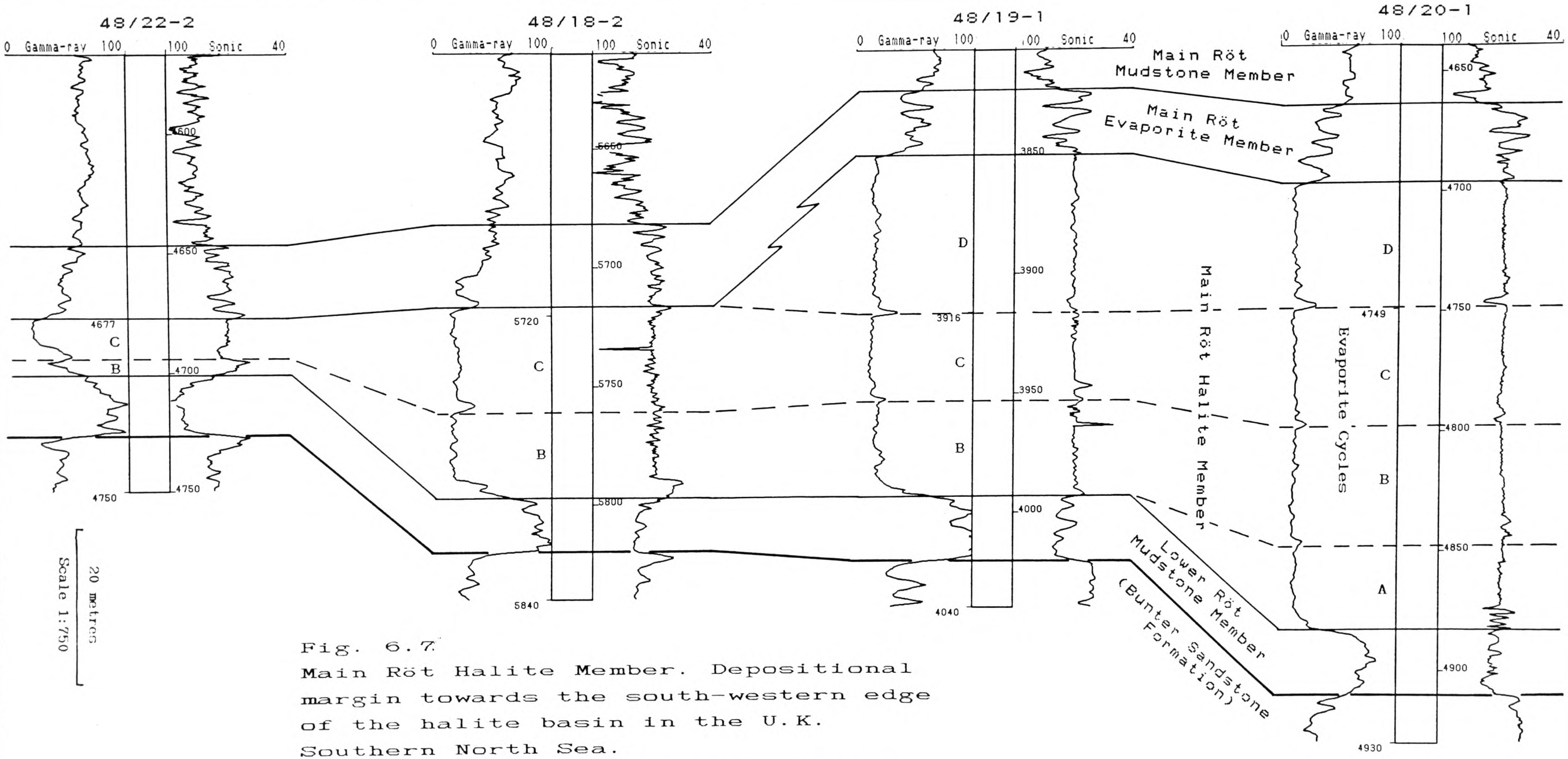


Fig. 6.7
Main Röt Halite Member. Depositional margin towards the south-western edge of the halite basin in the U.K. Southern North Sea.
Depositional margins are inferred where individual halite cycles extend beyond others. Cycle A was overstepped by Cycle B, which in turn was overstepped by Cycle C. Cycle D, however, shows a less extensive development.

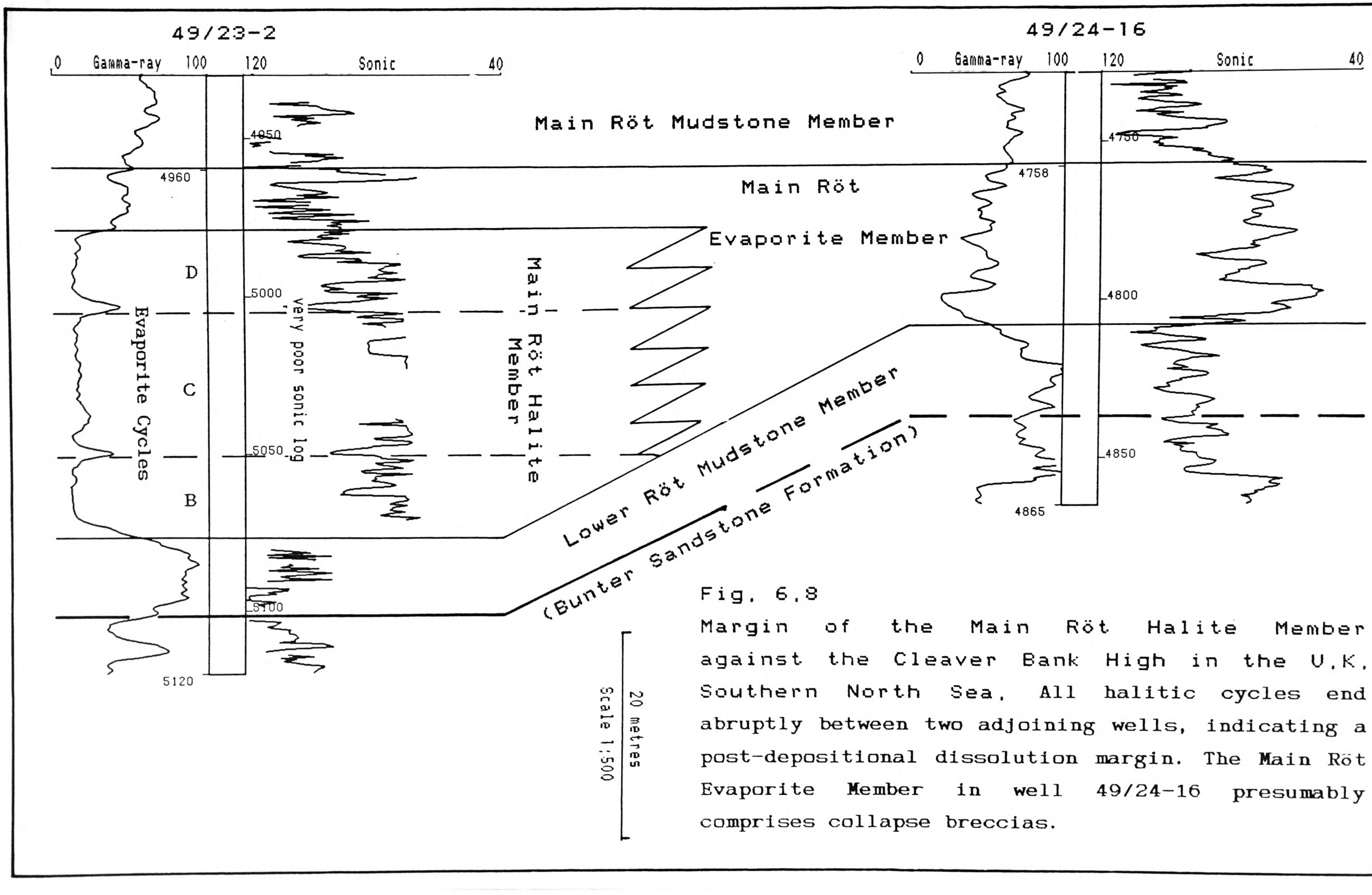


Fig. 6.8

Margin of the Main Röt Halite Member against the Cleaver Bank High in the U.K. Southern North Sea. All halitic cycles end abruptly between two adjoining wells, indicating a post-depositional dissolution margin. The Main Röt Evaporite Member in well 49/24-16 presumably comprises collapse breccias.

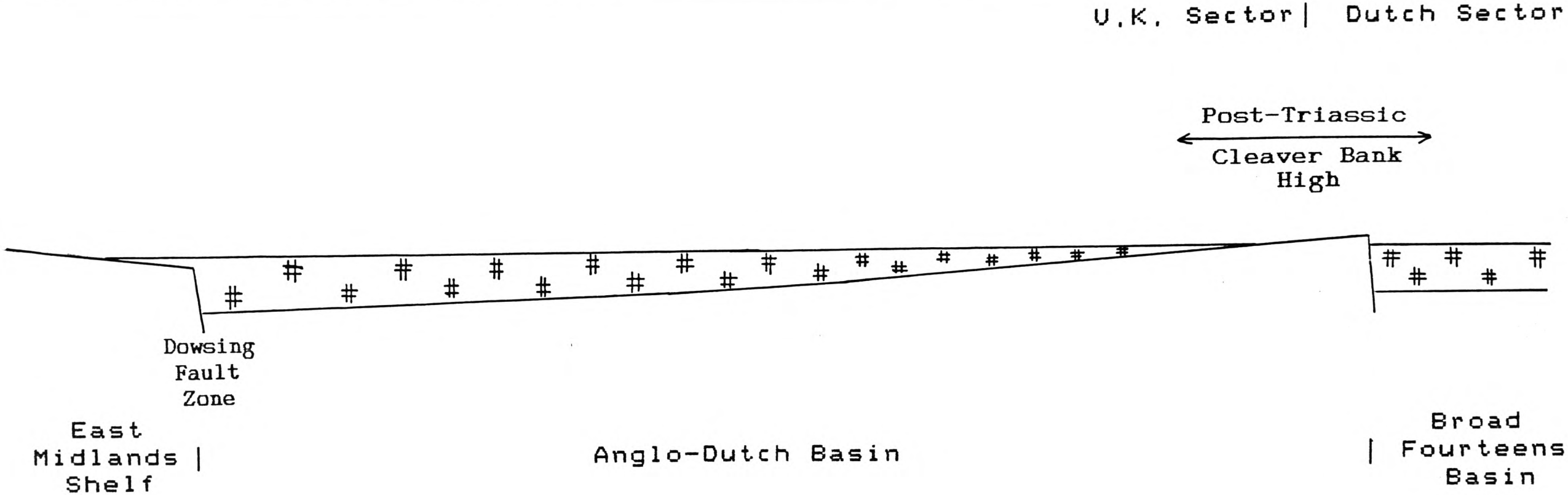


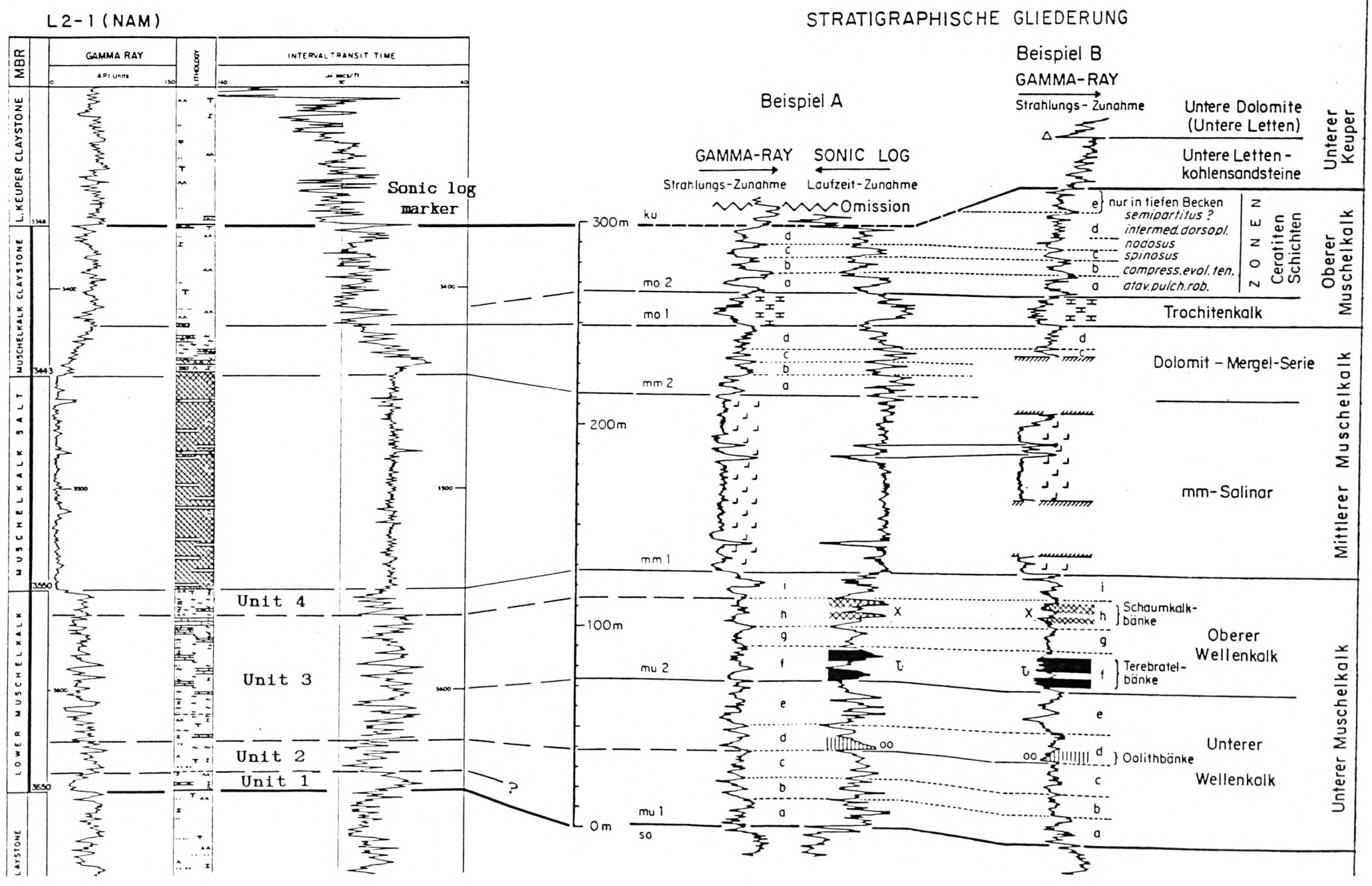
Fig. 6.9
Schematic cross-section across the U.K. Southern North Sea (Quadrants 48 and 49) during the deposition of Main Röt Halite Member Cycle B. In the Anglo-Dutch Basin, the Member thins towards the Broad Fourteens Basin, indicating a depositional margin. Superimposed on this is post-Triassic dissolution associated with the uplift and erosion of the Cleaver Bank High.

Fig. 6.10
Correlation of the Muschelkalk between the Dutch Southern North Sea and north Germany (amended from NAM/RGD 1980, encl. 11).

The four-fold subdivision of the Lower Muschelkalk (Muschelkalk Dolomitic Member) is tentatively extended to north Germany, where Unit 3 equates with the sequence containing high energy calcarenite banks.

The top of the Dowsing Dolomitic Formation, defined as the base of the 'sonic log marker', is here seen to equate with the Muschelkalk/Keuper boundary in north Germany.

Scale 1:3,300 (approx.)



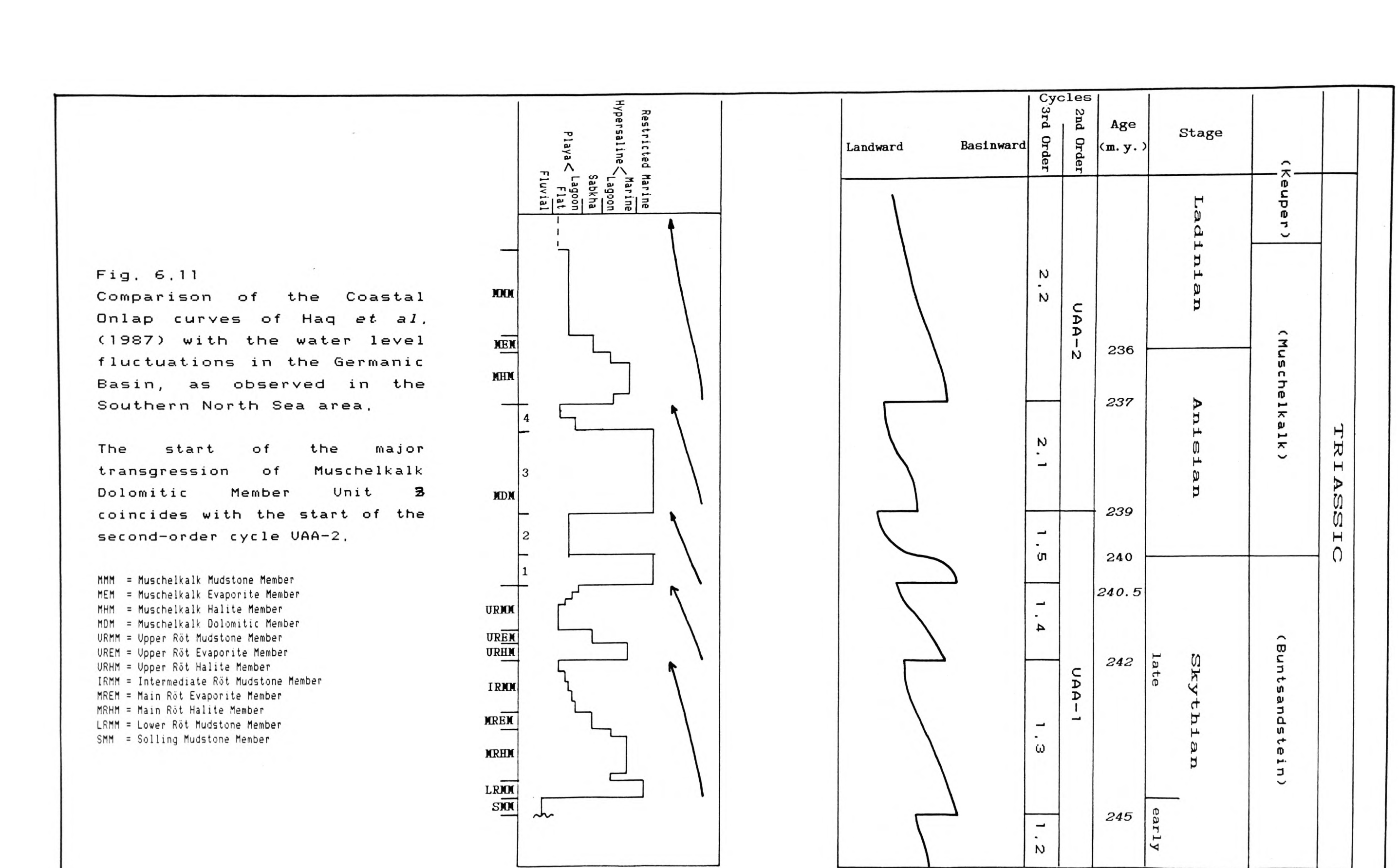
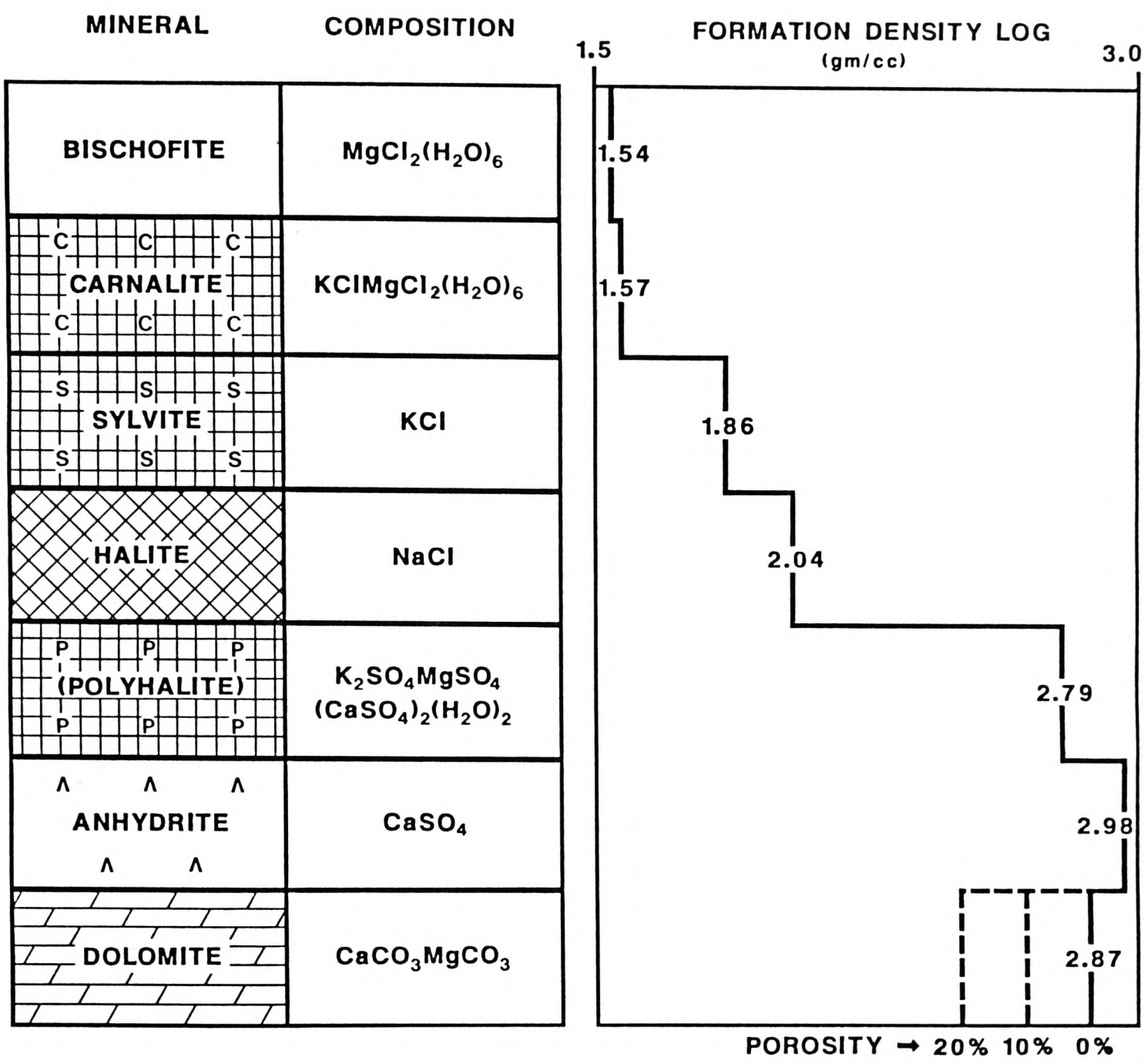


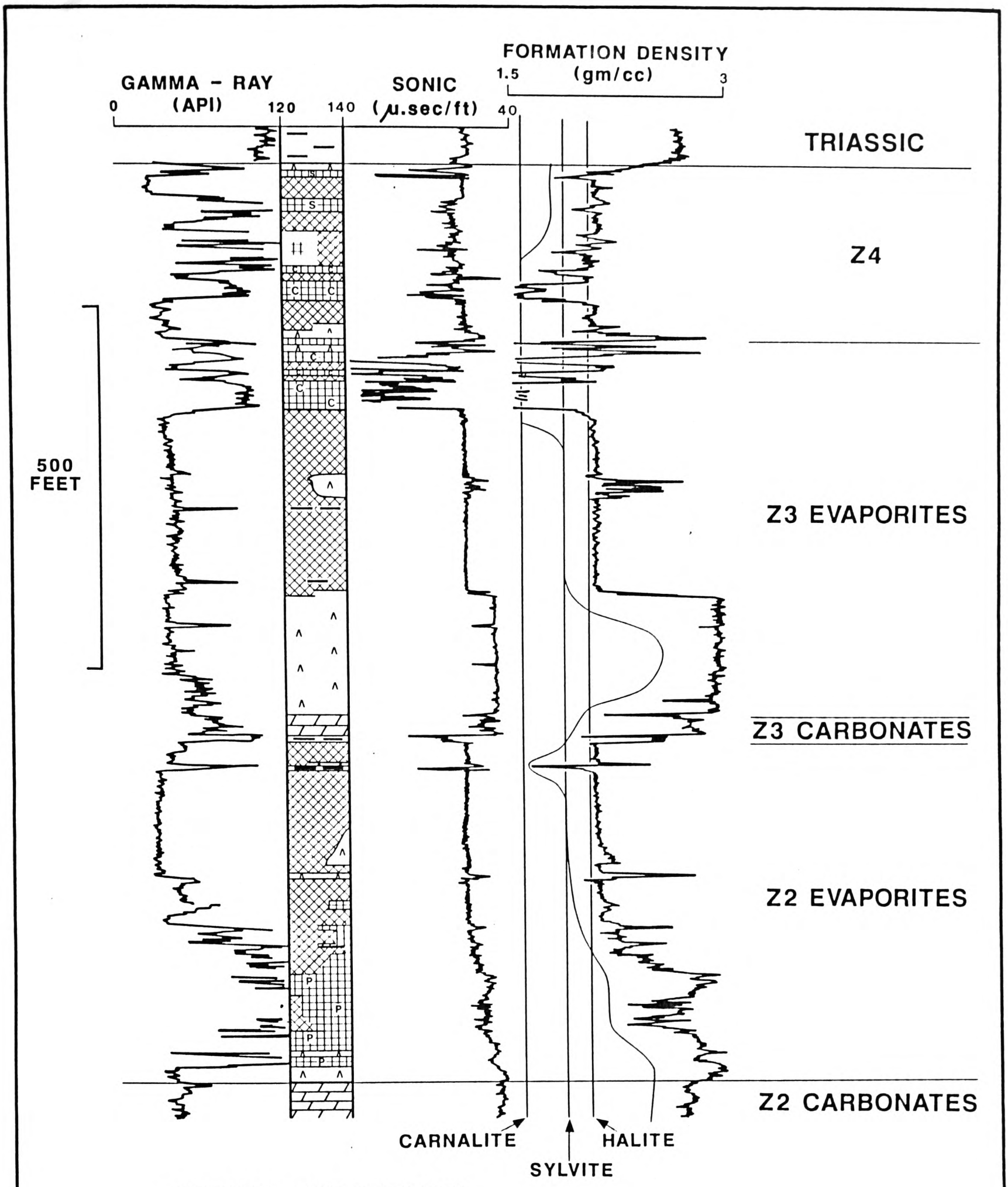
Fig. 6.11
Comparison of the Coastal Onlap curves of Haq *et al*, (1987) with the water level fluctuations in the Germanic Basin, as observed in the Southern North Sea area.

The start of the major transgression of Muschelkalk Dolomitic Member Unit **3** coincides with the start of the second-order cycle UAA-2.

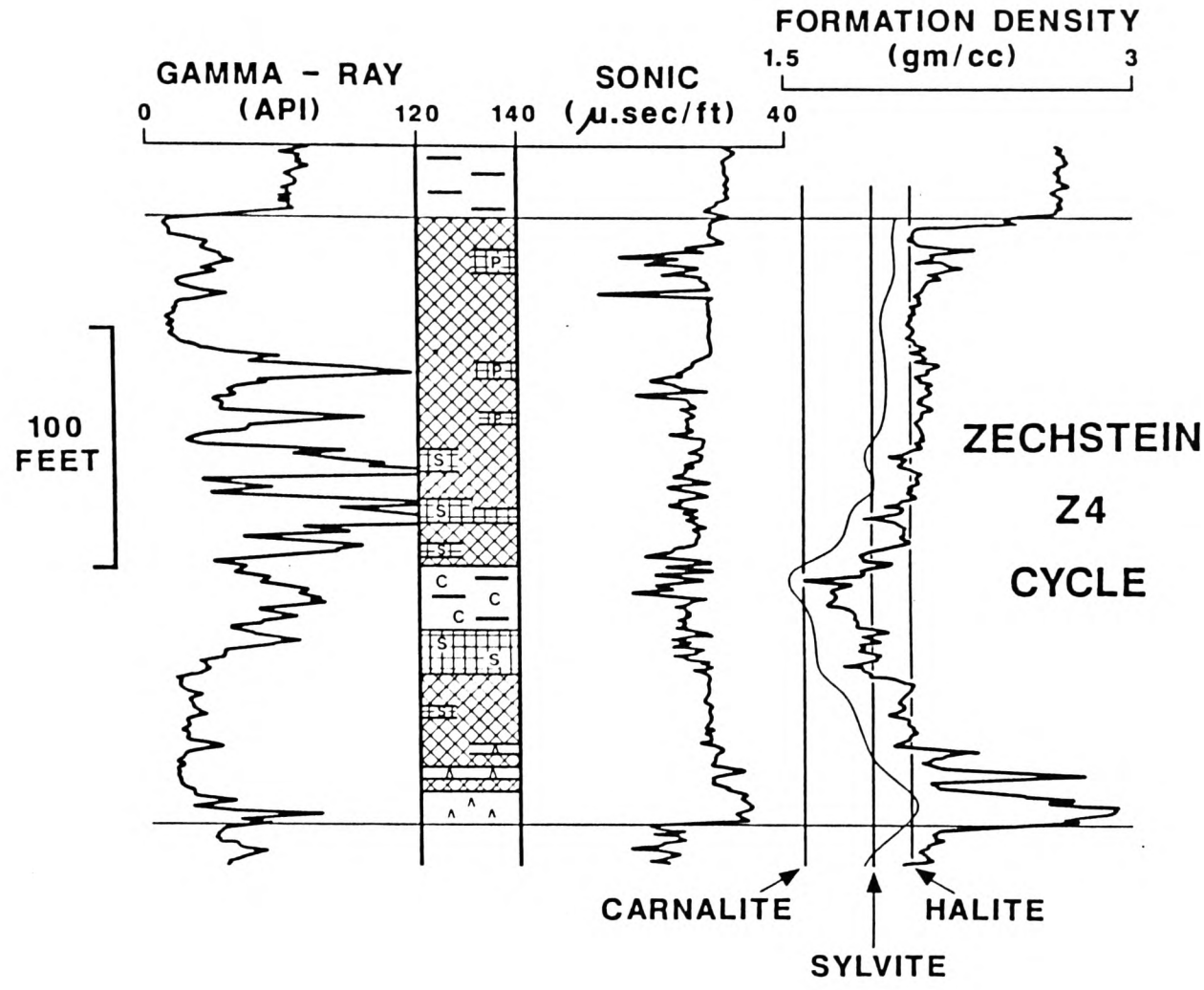
MMM = Muschelkalk Mudstone Member
MEM = Muschelkalk Evaporite Member
MHM = Muschelkalk Halite Member
MDM = Muschelkalk Dolomitic Member
URMM = Upper Röt Mudstone Member
UREM = Upper Röt Evaporite Member
URHM = Upper Röt Halite Member
IRMM = Intermediate Röt Mudstone Member
MREM = Main Röt Evaporite Member
MRHM = Main Röt Halite Member
LRMM = Lower Röt Mudstone Member
SMM = Solling Mudstone Member



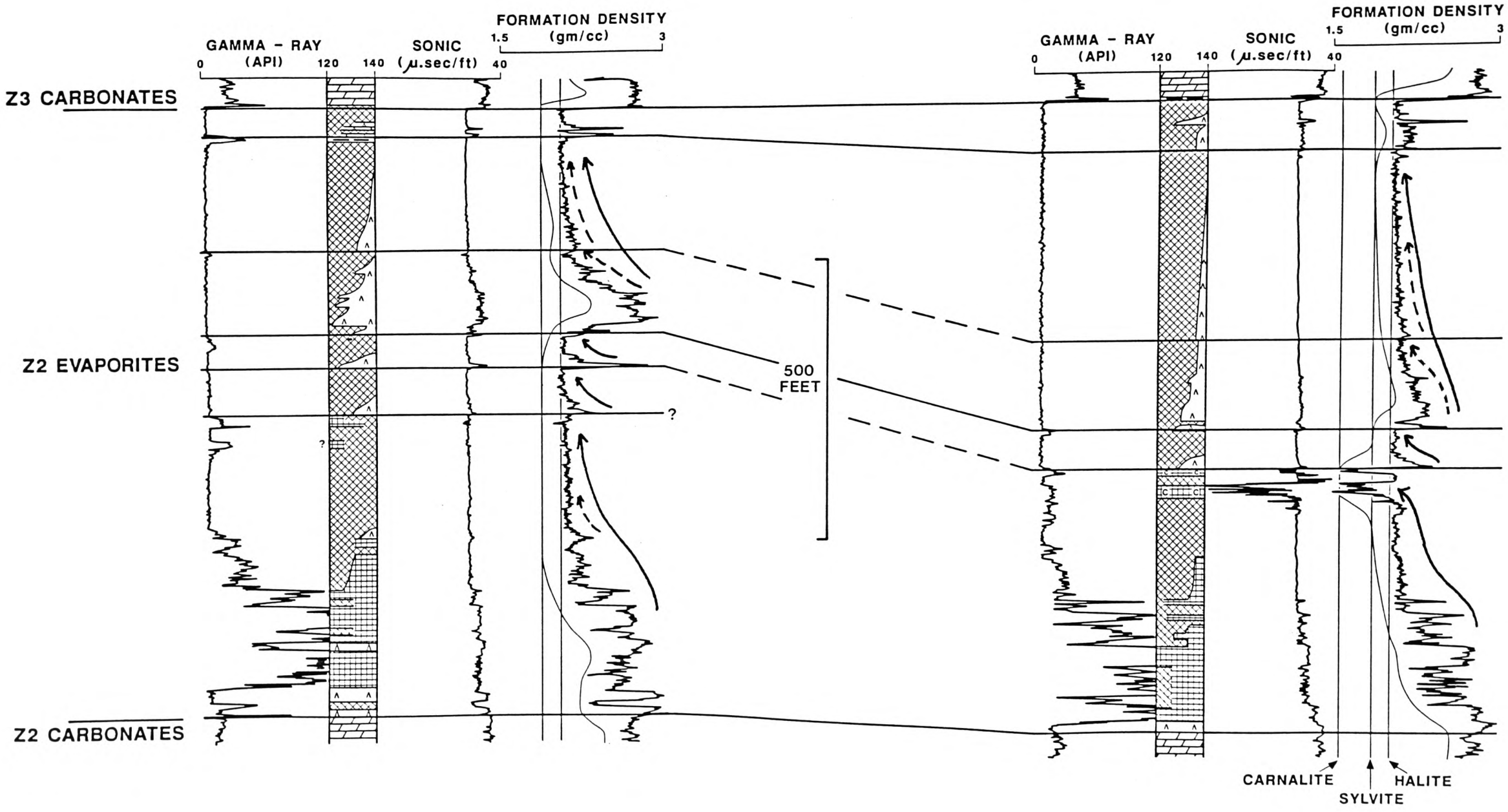
Appendix Fig. C.1
Relationship between the measured Formation Density and the evaporite facies (for pure minerals). The Formation Density (FDC) log reflects increases in salinity by a reduction in log density.



Appendix Fig. C.2
Cyclicity within the Zechstein evaporites identified on the FDC log. Minor salinity variations during halite deposition are also picked out by this log.

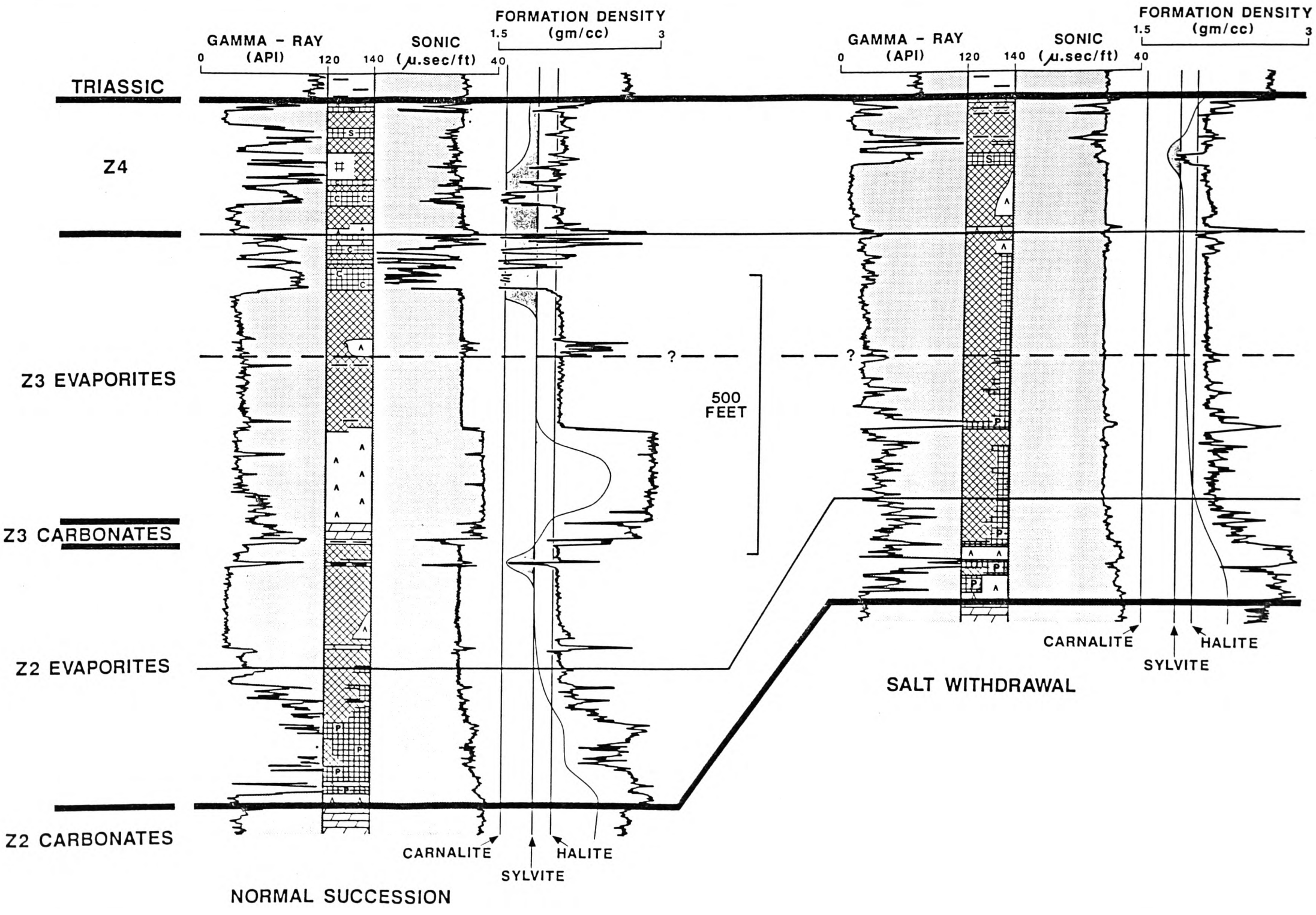


Appendix Fig. C.3
Detail of Appendix Fig. C.2, showing the symmetrical development of the Z4 Cycle. The FDC log identifies a gradual increase in salinity to the carnalite facies, followed by a gradual decrease to the end of the cycle.



Appendix Fig. C.4
Correlation of small-scale cyclicity in the
Z2 Halites - identified from the FDC log.

Appendix Fig. C.5
Use of the FDC log to define zones of Zechstein salt withdrawal. Correlation of minor evaporite cycles constrains the zone of salt movement. Wells 13 km apart.



PLATES

PLATES

'STAITHES-20' WELL

CORE PHOTOGRAPHS

PLATE 3.1 'Staithes-20' Depth: 2086'

Lower Röt Mudstone Member

Fine to medium grained sandstone from the base of the Member, containing mudstone clasts and disrupted layers. Scale in cms.

PLATE 3.2 'Staithes-20' Depth: 2083'

Lower Röt Mudstone Member

Generally unlaminated dolomitic mudstone with horizons of dolomitic siltstone or silty dolomite. Possible cross-lamination in the upper green zone. Water escape possibly produces wavy lamination in the lower zone. Scale in cms.



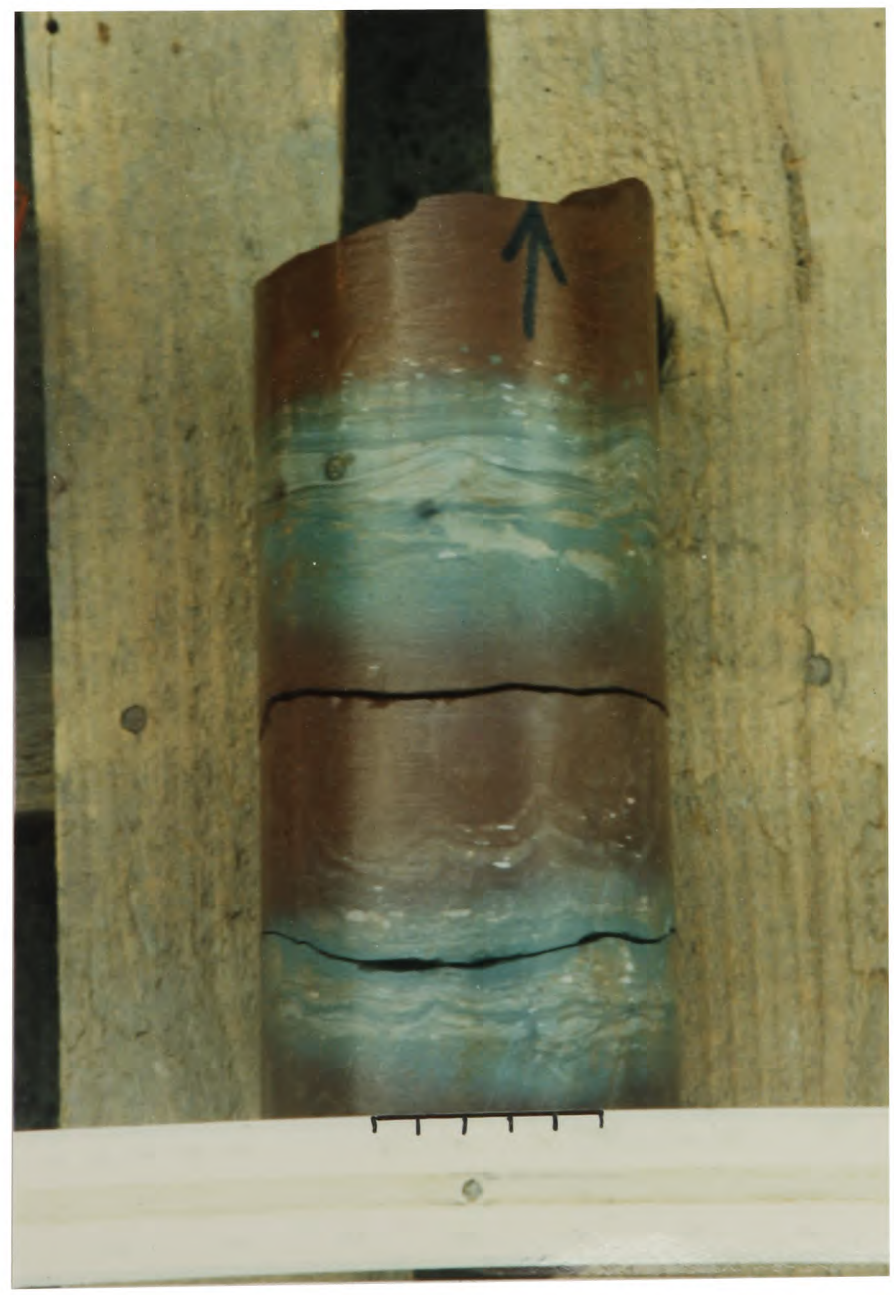


PLATE 3.1 'Staithes-20' Depth: 2086'

Lower Röt Mudstone Member

Fine to medium grained sandstone from the base of the Member, containing mudstone clasts and disrupted layers. Scale in cms.

PLATE 3.2 'Staithes-20' Depth: 2083'

Lower Röt Mudstone Member

Generally unlaminated dolomitic mudstone with horizons of dolomitic siltstone or silty dolomite. Possible cross-lamination in the upper green zone. Water escape possibly produces wavy lamination in the lower zone. Scale in cms.



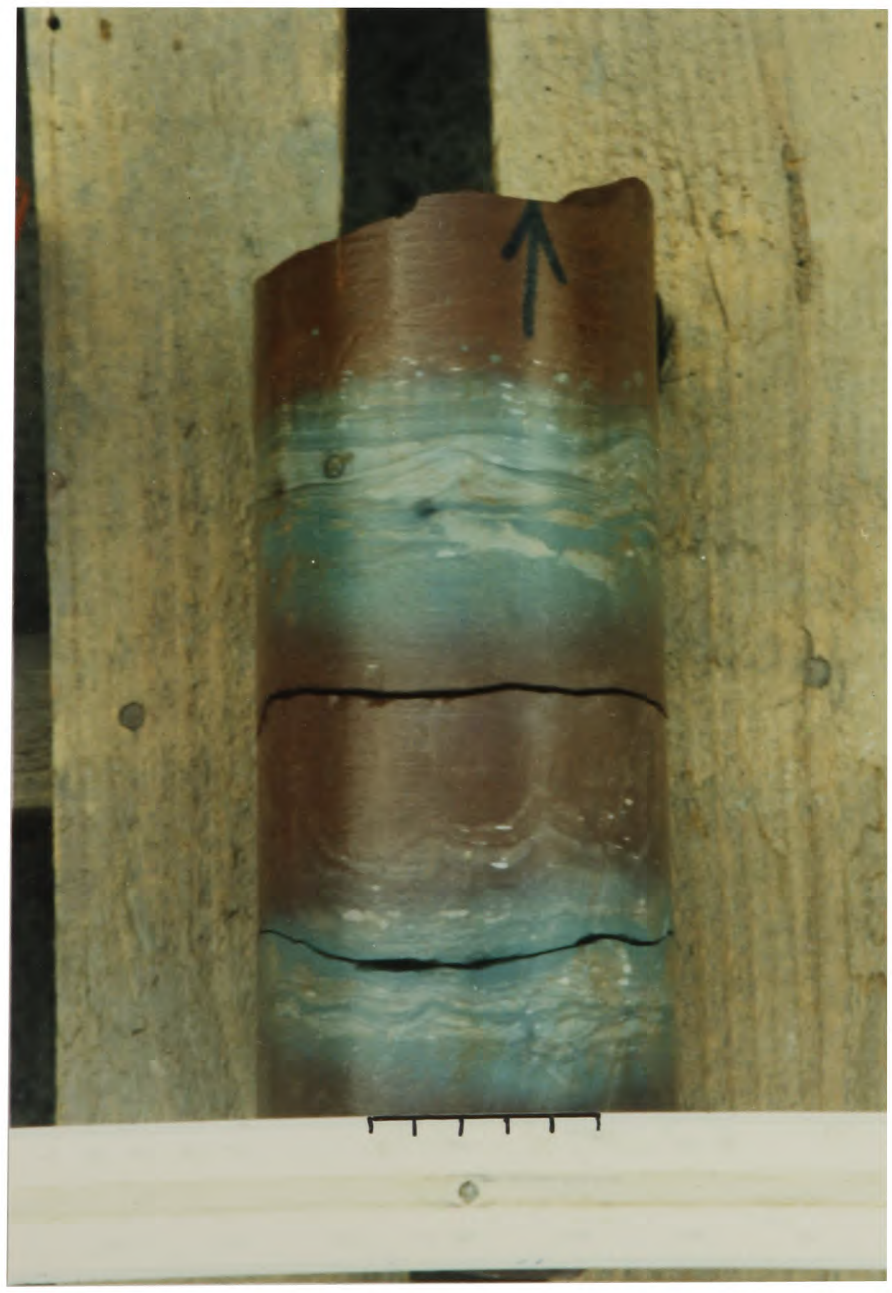


PLATE 3.3 'Staithes-20' Depths: 2100'-2063'

Bunter Sandstone Formation to Main Röt Evaporite Member

Abrupt colour change from the red-brown mudstones of the Lower Röt Mudstone Member to the green-grey dolomites and anhydrites of the basal Main Röt Evaporite Member. Younging from base to top, left to right. Corebox length approx. 3 metres.

PLATE 3.4 'Staithes-20' Depth: 2058'

Main Röt Evaporite Member

Halite dissolution collapse breccia, comprising light brown silty dolomites and anhydritic mudstones and siltstones. Scale in cms.



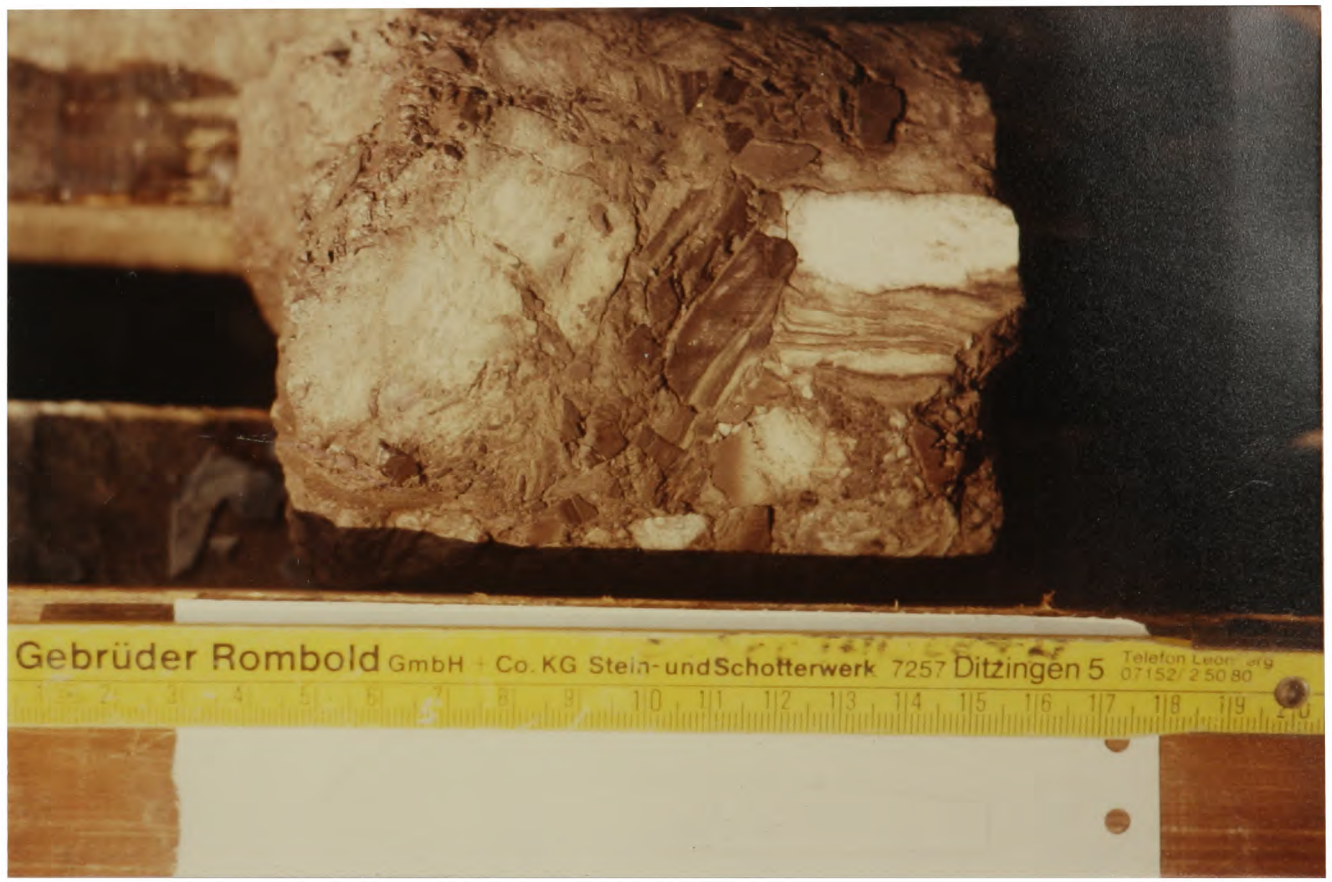

Gebrüder Rombold GmbH + Co. KG Stein- und Schotterwerk 7257 Ditzingen 5
Telefon
07152/ 25080

PLATE 3.5 'Staithes-20' Depth: 2030'

Intermediate Röt Mudstone Member

Laminated facies: Interbedded argillaceous dolomites and dolomitic mudstones. Possible loading on the base of a dolomite at 44 cm. Upper surfaces may be rippled (at 37 cm). Desiccation crack extends downwards from the top of the facies (at the top of the core). Scale in cms.

PLATE 3.6 'Staithes-20' Depth: 2024'

Intermediate Röt Mudstone Member

Laminated facies: Dolomite at the top has buckled, highly contorting the underlying laminated dolomitic mudstone. Asymmetrical nature of the buckling implies slumping. Scale in cms.





PLATE 3.7 'Staithes-20' Depth: 2011'

Intermediate Röt Mudstone Member

Laminated facies overlying blocky facies. Large-scale brecciation due to anhydrite veining. Scale in cms.

PLATE 3.8 'Staithes-20' Depth: 1980'

Intermediate Röt Mudstone Member

Laminated facies: Laminated dolomite (7-10 cm on scale) has been severely buckled by water escape. Upper surface was eroded flat before deposition of the succeeding interbedded dolomites and mudstones. Scale in cms.




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PLATE 3.9 'Staithes-20' Depth: 1973'

Upper Röt Evaporite Member

Possible sabkha cycle: Laminated dolomite overlain by mottled anhydritic mudstone, followed by a more massive mudstone. Scale in cms.

PLATE 3.10 'Staithes-20' Depth: 1906'

Upper Röt Mudstone Member

Blocky facies: Desiccation cracks on the base of a dolomitic mudstone. Scale in cms.





PLATE 3.11 'Staithes-20' Depth: 1896'

Upper Röt Mudstone Member

Laminated facies (dolomitic/anhydritic mudstones) at the base, desiccated at its upper contact with the overlying blocky facies (at 40 cm). Laminated facies again present in the centre of the core. Scale in cms.

PLATE 3.12 'Staithes-20' Depth: 1869'

Muschelkalk Dolomitic Member - Unit 1

Laminated facies: Argillaceous dolomites with thin dolomitic mudstones. Ripple lamination at 37 cm. Scale in cms.



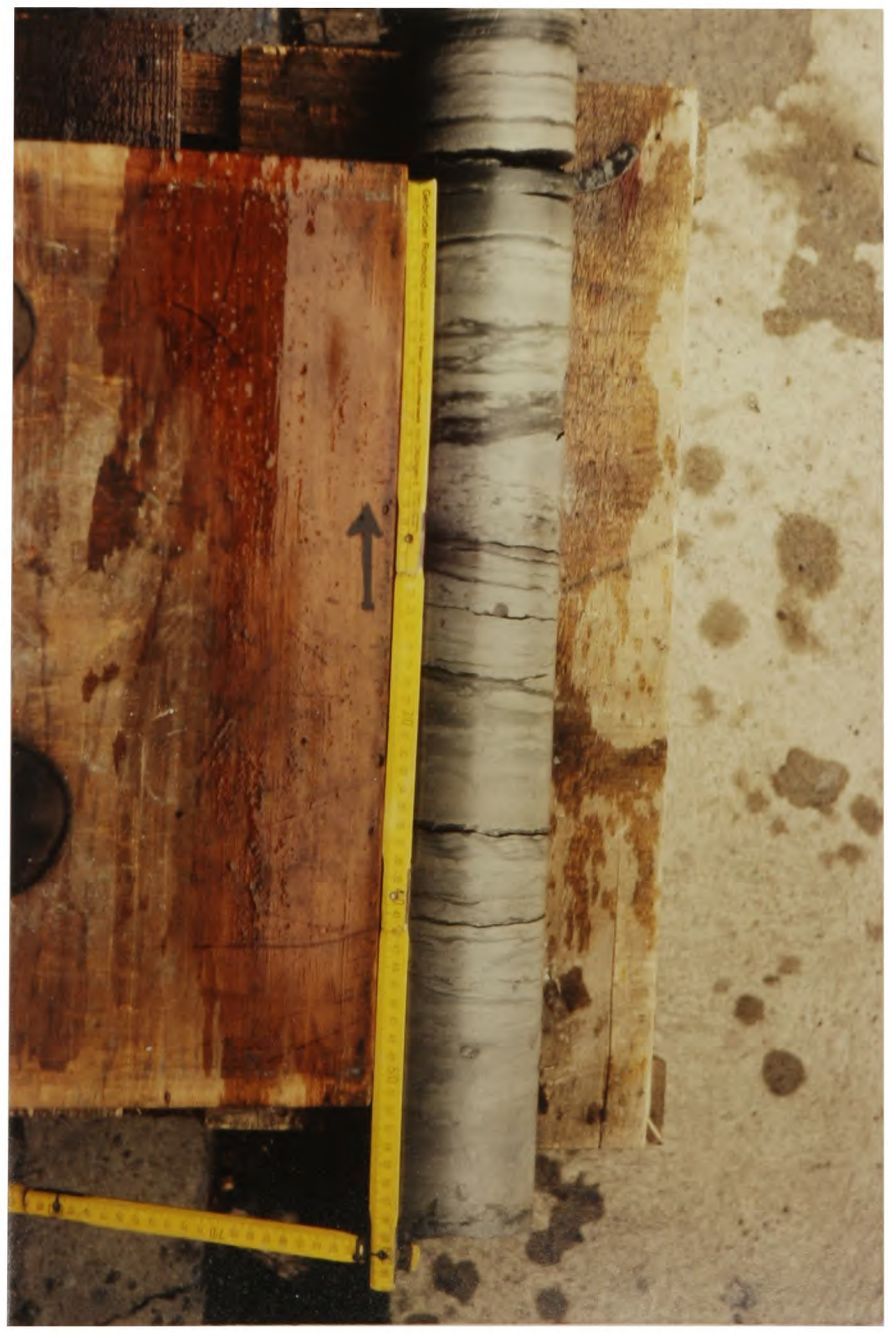

PLATE 3.13 'Staithes-20' Depth: 1867'

Muschelkalk Dolomitic Member - Unit 1

Laminated facies: Displacive growth of nodular anhydrite within a mudstone layer has buckled the overlying lamination (around 21 cm). This has subsequently been eroded flat prior to the deposition of the laminated dolomite at 24 cm. Scale in cms.

PLATE 3.14 'Staithes-20' Depth: 1863'

Muschelkalk Dolomitic Member - Unit 1

Laminated facies: Loading on the base of an argillaceous dolomite. Scale in cms.

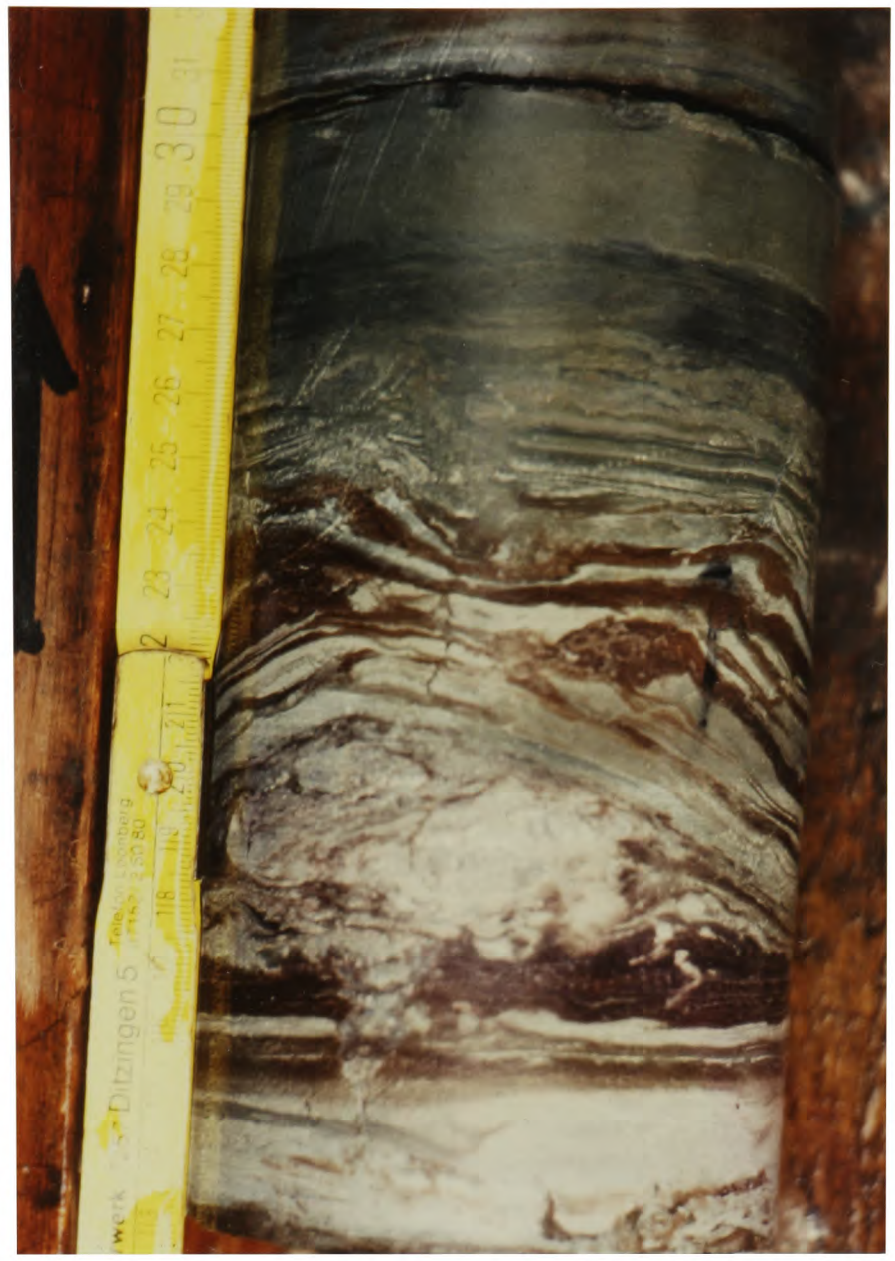
Ditzingen 5


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PLATE 3.15 'Staithes-20' Depth: 1850'

Muschelkalk Dolomitic Member - Unit 2

Blocky facies: Anhydrite nodules in unlaminated dolomitic mudstone, coalescing to form chicken-wire fabric. Overlain by laminated facies. Scale in cms.

PLATE 3.16 'Staithes-20' Depth: 1848'

Muschelkalk Dolomitic Member - Unit 2

Laminated facies overlain by blocky facies: Desiccation crack with turned up edges penetrates down from the top of the laminated facies. Large anhydrite nodule immediately above this may result from the subsequent upward migration of sulphate-rich fluids through the crack. Scale in cms.


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PLATE 3.17 'Staithes-20' Depth: 1830'

Muschelkalk Dolomitic Member - Unit 3

Thin development of the laminated facies overlain by the blocky facies, with laminated facies again at the top of the core. Vein anhydrite causes brecciation. Scale in cms.

PLATE 3.18 'Staithes-20' Depth: 1790'

Muschelkalk Dolomitic Member - Unit 3

Laminated facies: Argillaceous anhydritic dolomites with inter-bedded dolomitic mudstone. Water escape structure at 28 cm is infilled with anhydrite, due to migrating sulphate-rich brines. Further evidence of water escape at 38 cm. Scale in cms.




23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41

PLATE 3.19 'Staithes-20' Depth: 1764'

Muschelkalk Dolomitic Member - Unit 4

Blocky facies: Brecciated anhydritic mudstone. Vertical mudstone-filled fractures (desiccation?) occur throughout the core (left-side at 20-30 cm; right-side at 32-38 cm; left and centre at 43-47 cm). Scale in cms.

PLATE 3.20 'Staithes-20' Depth: 1750'

Muschelkalk Evaporite Member

Base of the Member is the base of an irregular mottled anhydritic dolomite (near 1750'), which is overlain by a mottled dolomitic, anhydritic mudstone. Scale in cms.





PLATE 3.21 'Staithes-20' Depth: 1735'

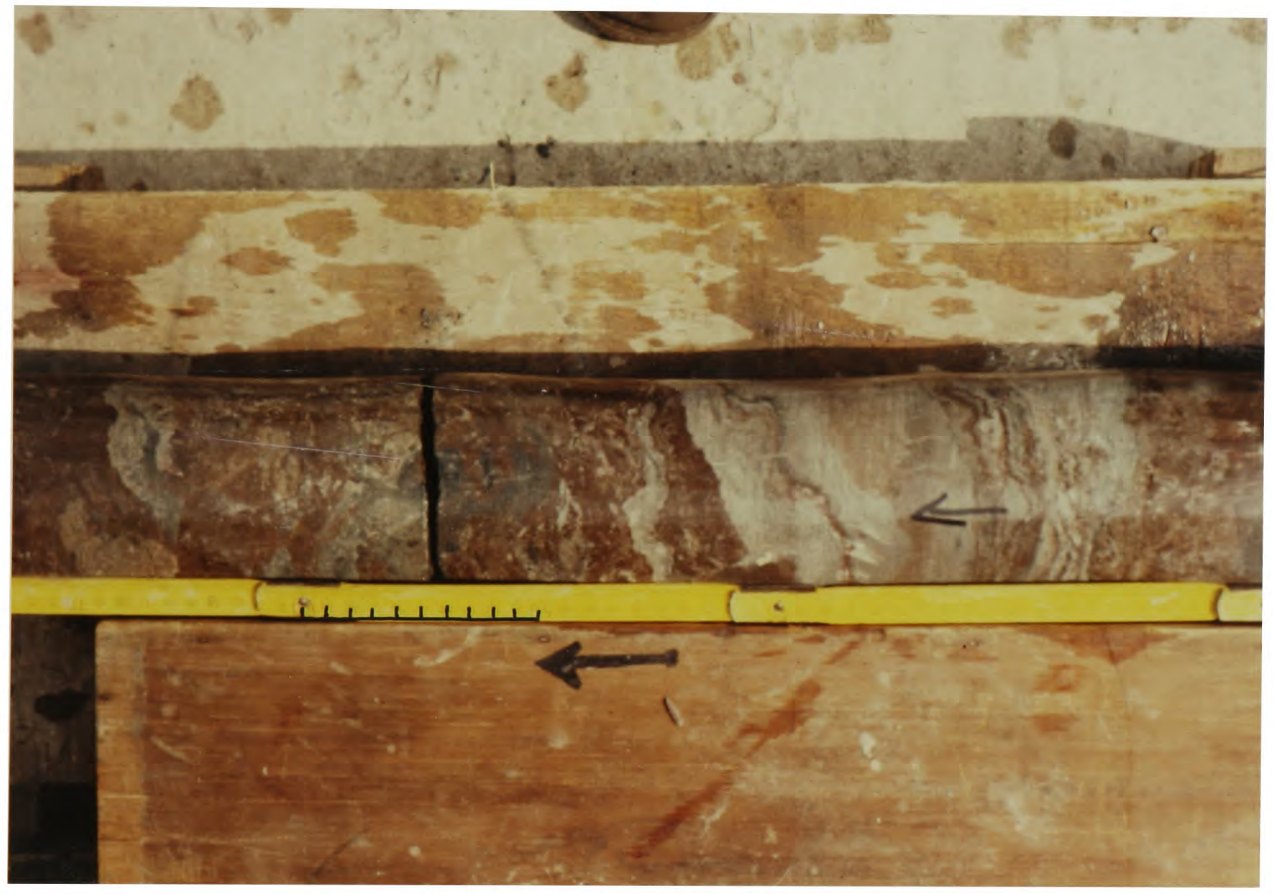
Muschelkalk Evaporite Member

Light brown-grey nodular to entrolithic anhydrite in red-brown mottled dolomitic mudstone. Scale in cms.

PLATE 3.22 'Staithes-20' Depth: 1639'

Muschelkalk Mudstone Member

Blocky and mottled mudstone facies: Brecciated (desiccated?) mottled facies at base (below 1640') passes upwards into the blocky facies, with anhydrite nodules coalescing at the top of the core. Scale in cms.



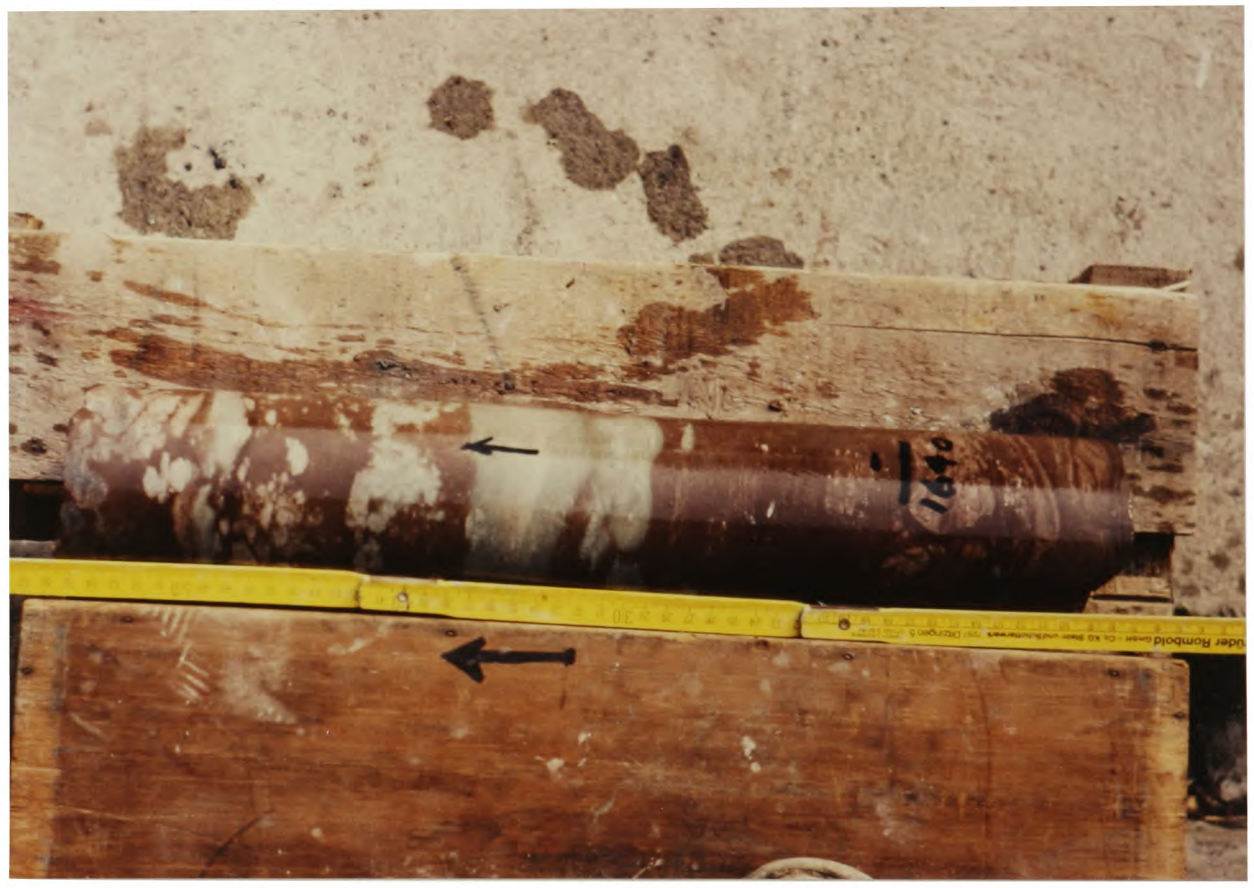


PLATE 3.23 'Staithes-20' Depth: 1618'

Muschelkalk Mudstone Member

Mottled facies: Light brown anhydritic mudstone; horizontal and vertical fractures infilled with dark brown mudstone; faintly nodular appearance. Origin of facies unknown. Scale in cms.

PLATE 3.24 'Staithes-20' Depth: 1587'

Muschelkalk Mudstone Member

Anhydritic mudstone, with anhydrite nodules forming chicken-wire fabric. Abruptly overlain by massive mudstone. Close to the top of the Member. Scale in cms.





PLATES

KIRTON BRICKWORKS

PLATE 4.1 Kirton Brickworks

Lower part of Zone 1 (two metre scale in the centre of the plate)

PLATE 4.2 Kirton Brickworks

Zone 1 and the lower part of Zone 2: Contact is light band about two thirds of the way up the face. Height of the quarry face is about 17 metres.



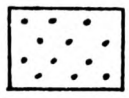


PLATE 4.3 Kirton Brickworks

Zone 3: Base of the Zone is just below the base of the exposure. Height of the quarry face about 10 metres.



KEY TO INTERPRETED LITHOLOGY LOGS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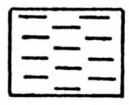
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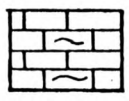
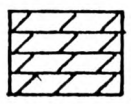

LIMESTONE (Marly)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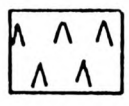
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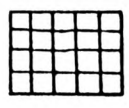
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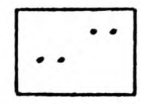
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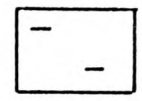
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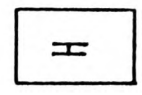
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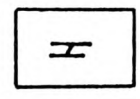
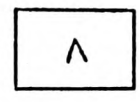

Dolomitic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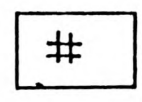
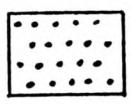
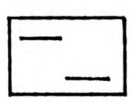
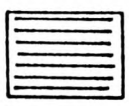
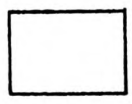

Halitic

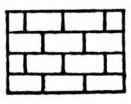
KEY TO PERCENTAGE CUTTINGS LOGS

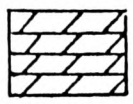

SANDSTONE - Varies from light grey-white to dark brown, but is generally light orange-brown, medium grained and well-sorted.

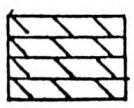

MUDSTONE - Red-orange-brown mudstone, occasionally dark red-purple, silty.

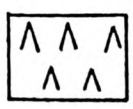

MUDSTONE - Light green to green-grey. Usually seen as a mottling of the red-brown mudstone.

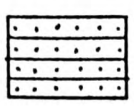

SHALE - Dark grey, occasionally calcareous. Probably Liassic cavings.


LIMESTONE - Light grey, marly. Not found in the U.K. Sector wells.


DOLOMITE - Light grey, generally microcrystalline occasionally coarser, marly (impure?).


DOLOMITE - Light grey, hard, coarsely crystalline. Distinguishable from above dolomite only in well 53/3-1 (encl. Well J).


ANHYDRITE - Generally white amorphous blebs in red-browm and green-grey mudstone, occasionally laminated.


HALITE - Milk-white to yellow-white, occasionally yellow to yellow-brown.

Key to ENCLOSURE WELLS A to N

ENCLOSURE WELLS

0 Gamma-ray (API) 120 | INTERPRETED LITHOLOGY | 140 Sonic (Δt) 40 | 1.95 FDC (gm/cc) 2.95 | 45 SNP (LPU) -15

3610

Sonic log marker

3700

3800

3850

3900

3950

4000

4050

4100

4150

4200

4250

4300

4350

4400

4450

4500

4550

4600

4650

4700

4750

4800

4850

4900

Severe borehole washout

FDC

SNP

Unit 4

Unit 3

Unit 2

Unit 1

F

E

D

C

B

A

Evaporite Cycles

50 metres

(Dudgeon Salliferous Formation)

Muschelkalk Mudstone Member

Muschelkalk Evaporite Member

Muschelkalk Halite Member

Muschelkalk Dolomitic Member

Upper Röt Mudstone Member

Upper Röt Evaporite Member

Intermediate Röt Mudstone Member

Main Röt Evaporite Member

Main Röt Halite Member

Lower Röt Mudstone Member

(Bunter Sandstone Formation)

Interpreted lithologies based on the MID-Plot (see text)

Dowsing Dolomitic Formation Type Well

WELL 48/12-1

ENCL. WELL A

Scale 1:1000

Gamma-ray (API) 0 120

COLOUR

CORE LOG

CYCLES

CROSS-LAMINATION/RIPPLES

LOAD STRUCTURES

WATER ESCAPE STRUCTURES

ANHIDRITE NODULES

DESICCATION CRACKS

1.95 FDC (gm/cc) 2.95

45 SNP (LPU) -15

100 Sonic (At) 50

Dudgeon Salliferous Formation

Muschelkalk Mudstone Member

Possible top Muschelkalk Evaporite Member

Muschelkalk Evaporite Member

Unit 4

Muschelkalk Dolomitic Member

Unit 3

Unit 2

Unit 1

No Core

?

Upper Röt Mudstone Member

Upper Röt Evaporite Member

Intermediate Röt Mudstone Member

SNP

FDC

Main Röt Evaporite Member

Lower Röt Mudstone Member

Sunter Sandstone Formation

1560 1580 1600 1620 1640 1660 1680 1700 1720 1740 1760 1780 1800 1820 1840 1860 1880 1900 1920 1940 1960 1980 2000 2020 2040 2060 2080 2100

Gamma-ray and sonic logs show a 0.5 to 1 metre shift w.r.t. to the core and FDC/SNP logs.

COLOUR

CORE LOG

CYCLES

SEDIMENTARY STRUCTURES (see top)

Red-Brown

Interlaminated Green-Grey/Red-Brown

Green-Grey

Mottled (?anhydritic?) Mudstone

Silty Mudstone

Argillaceous Dolomite

Fine/Medium Sandstone

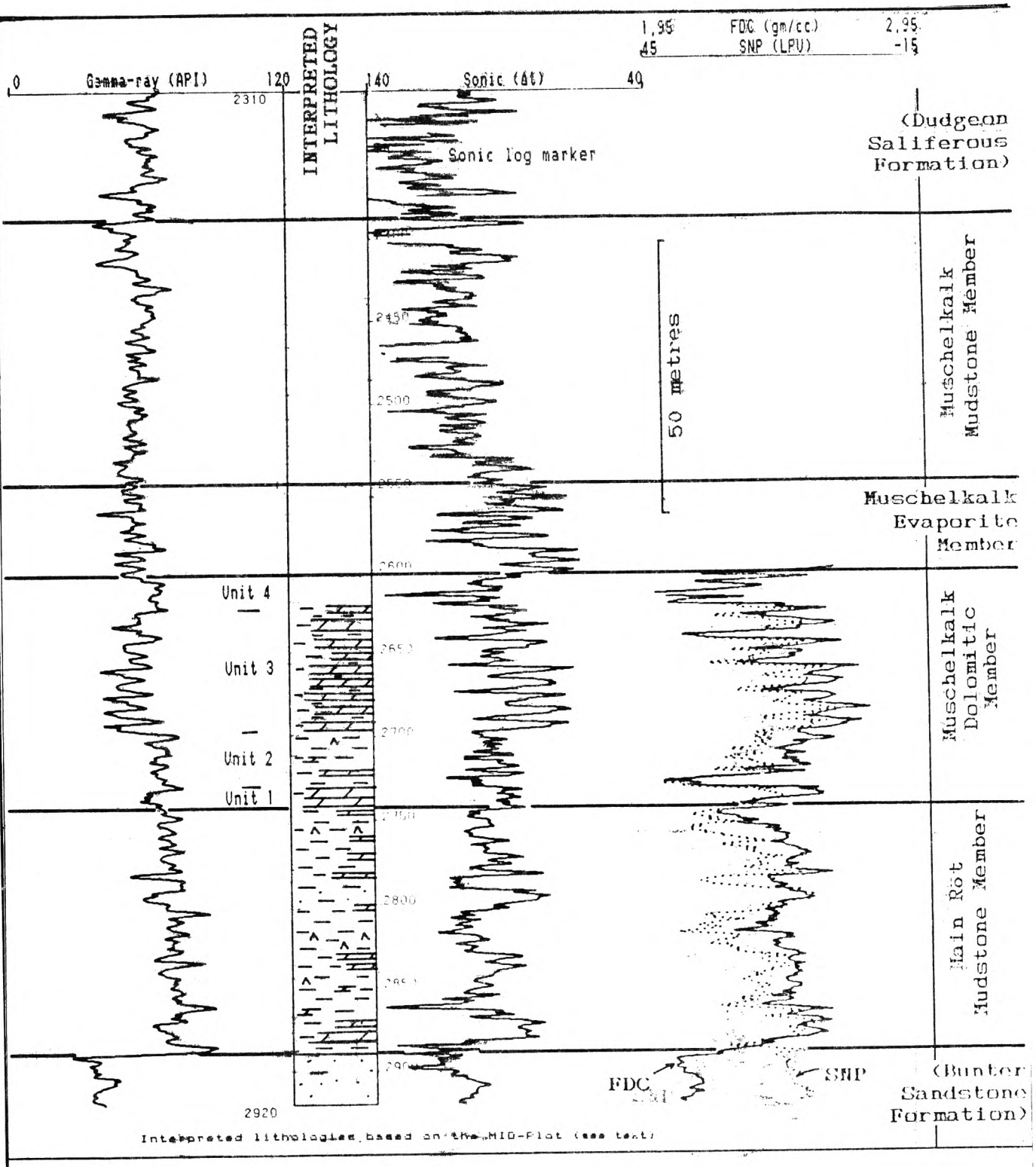
Dowsing Dolomitic Formation

Reference Well

WELL STAITHES-20

ENCL. WELL B

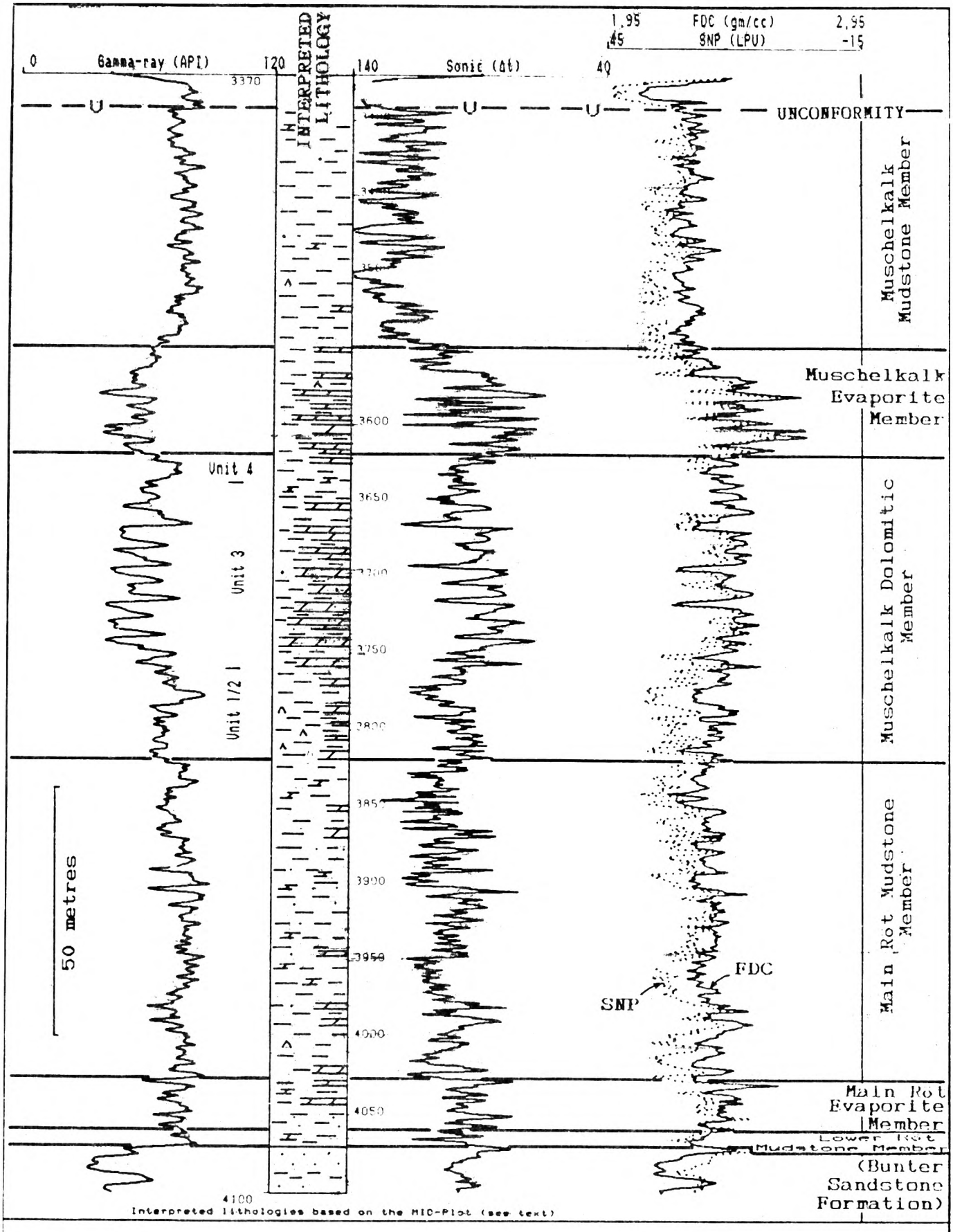
Scale 1:400



WELL 52/5-2

ENCL. WELL C

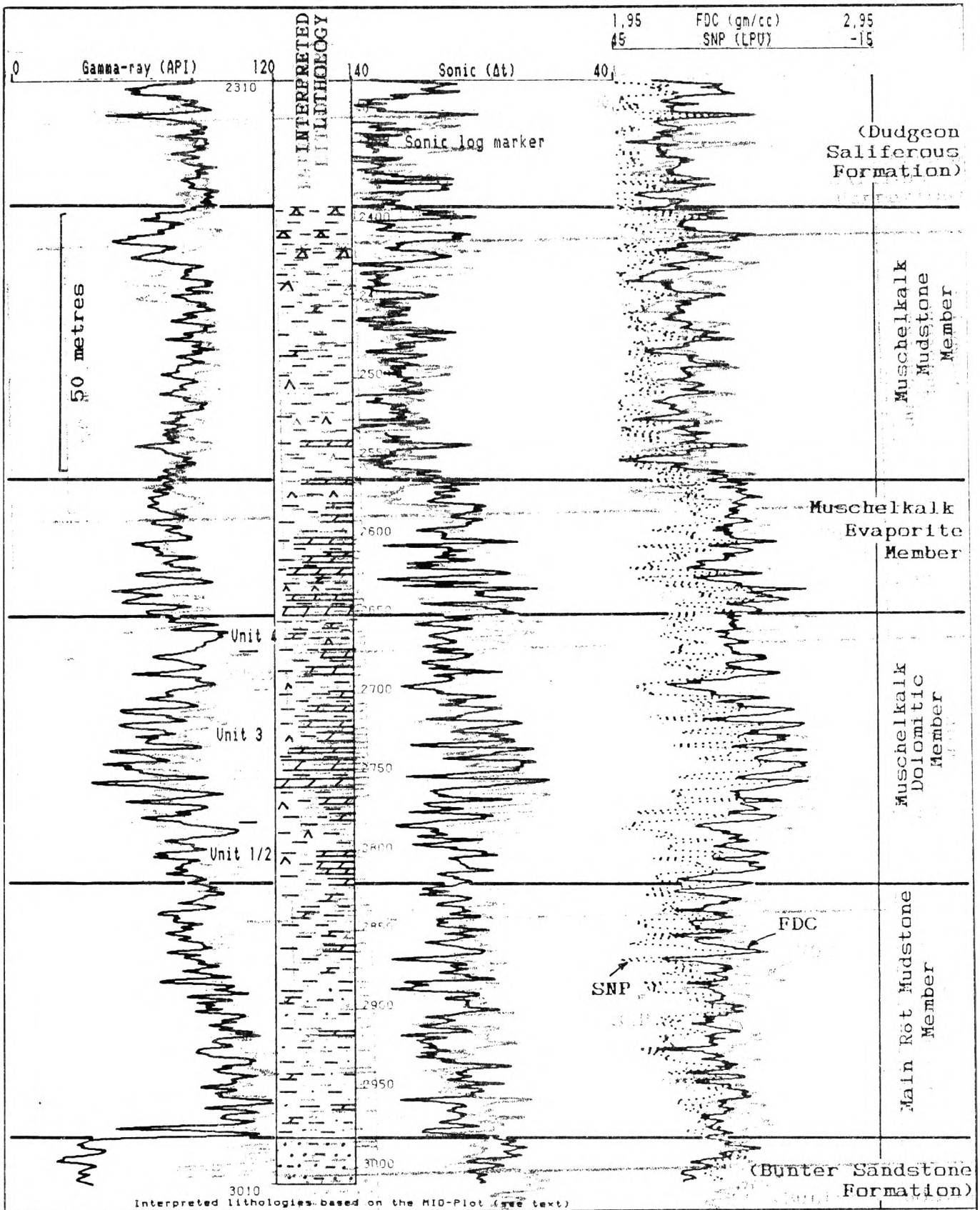
Scale 1:1000



WELL 53/4-4

Scale 1:1000

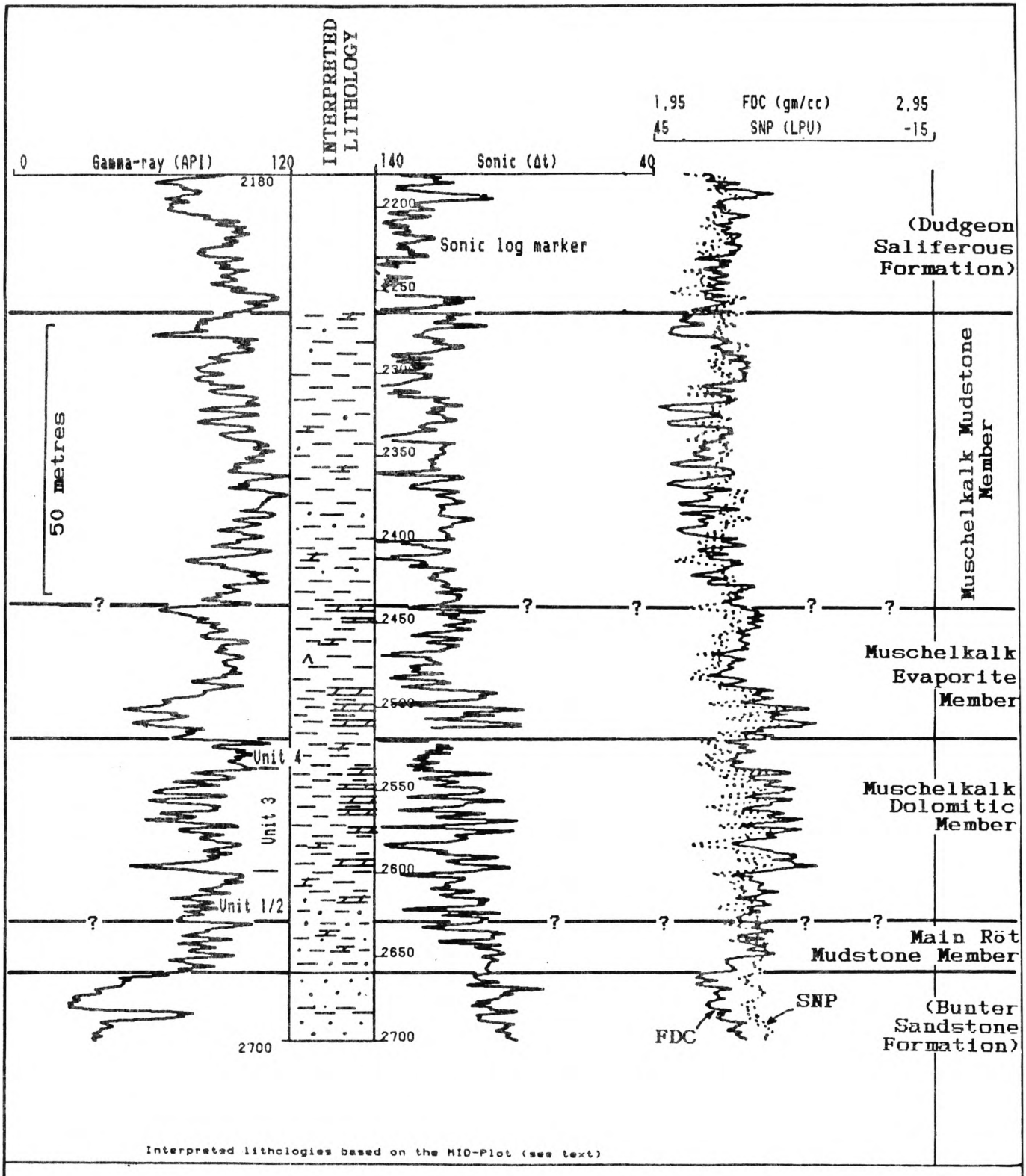
ENCL. WELL D



WELL 53/7-2

Scale 1:1000

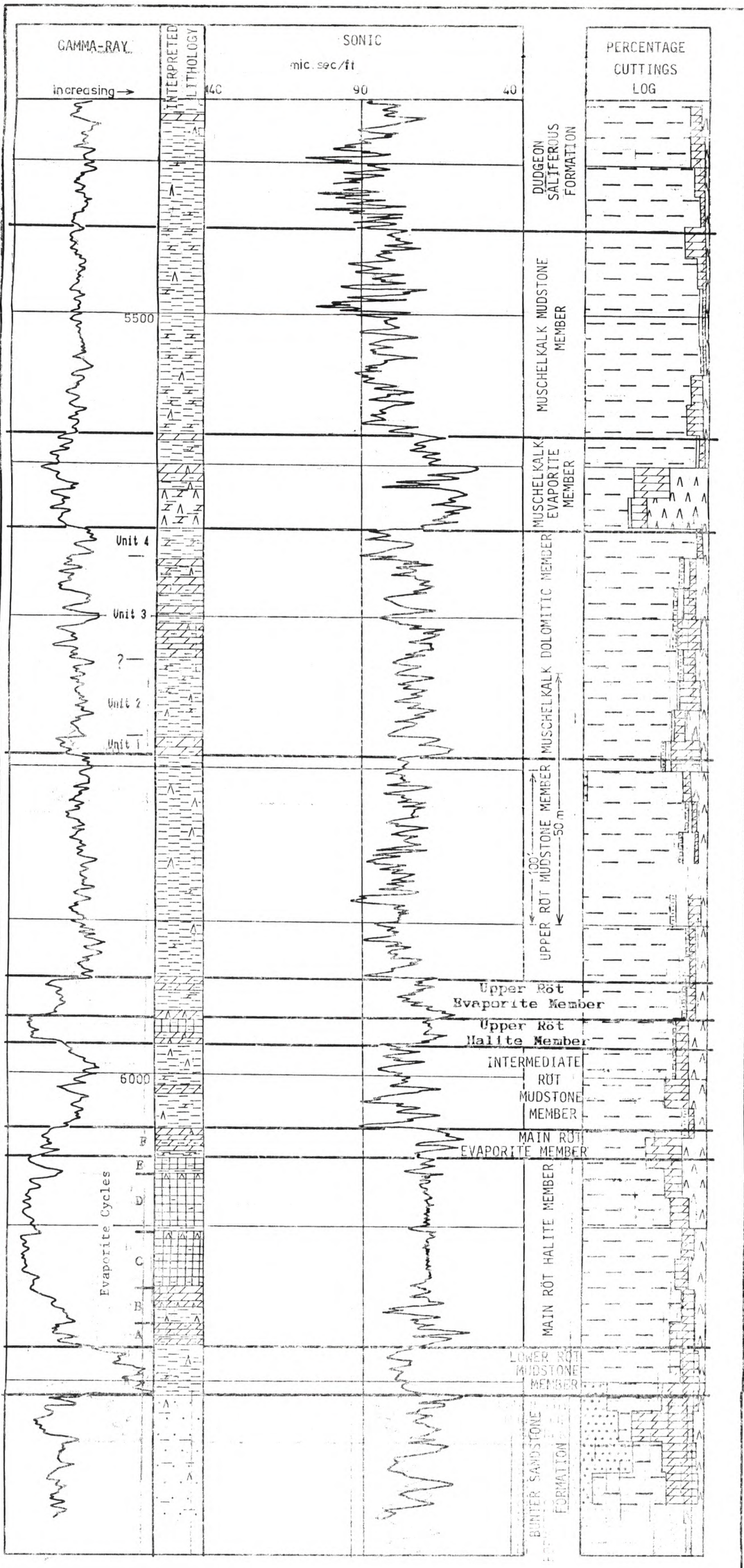
ENCL. WELL E



WELL 53/12-3

Scale 1:1000

ENCL. WELL F



WELL 42/28-2

Scale 1:1000 (approx.)

Encl. Well G

GAMMA-RAY

Increasing →

INTERPRETED LITHOLOGY

Resistivity (Laterolog)

ρ 5 10 ohms m²/m

PERCENTAGE CUTTINGS LOG

3500

4000

4500

4500

Unit 4

Unit 3

Unit 2

Unit 1

*

Evaporite Cycles

F

E

D

C

B

DUDGEON SALIFEROUS FORMATION

MUSCHELKALK MUDSTONE MEMBER

MUSCHELKALK EVAPORITE MEMBER

MUSCHELKALK HALITE MEMBER

MUSCHELKALK DOLOMITIC MEMBER

UPPER RÖT MUDSTONE MEMBER

50 meters

UPPER RÖT-EVAPORITE MEMBER

INTERMEDIATE RÖT MUDSTONE MEMBER

MAIN RÖT EVAPORITE MEMBER

MAIN RÖT HALITE MEMBER

LOWER RÖT MUDSTONE MEMBER

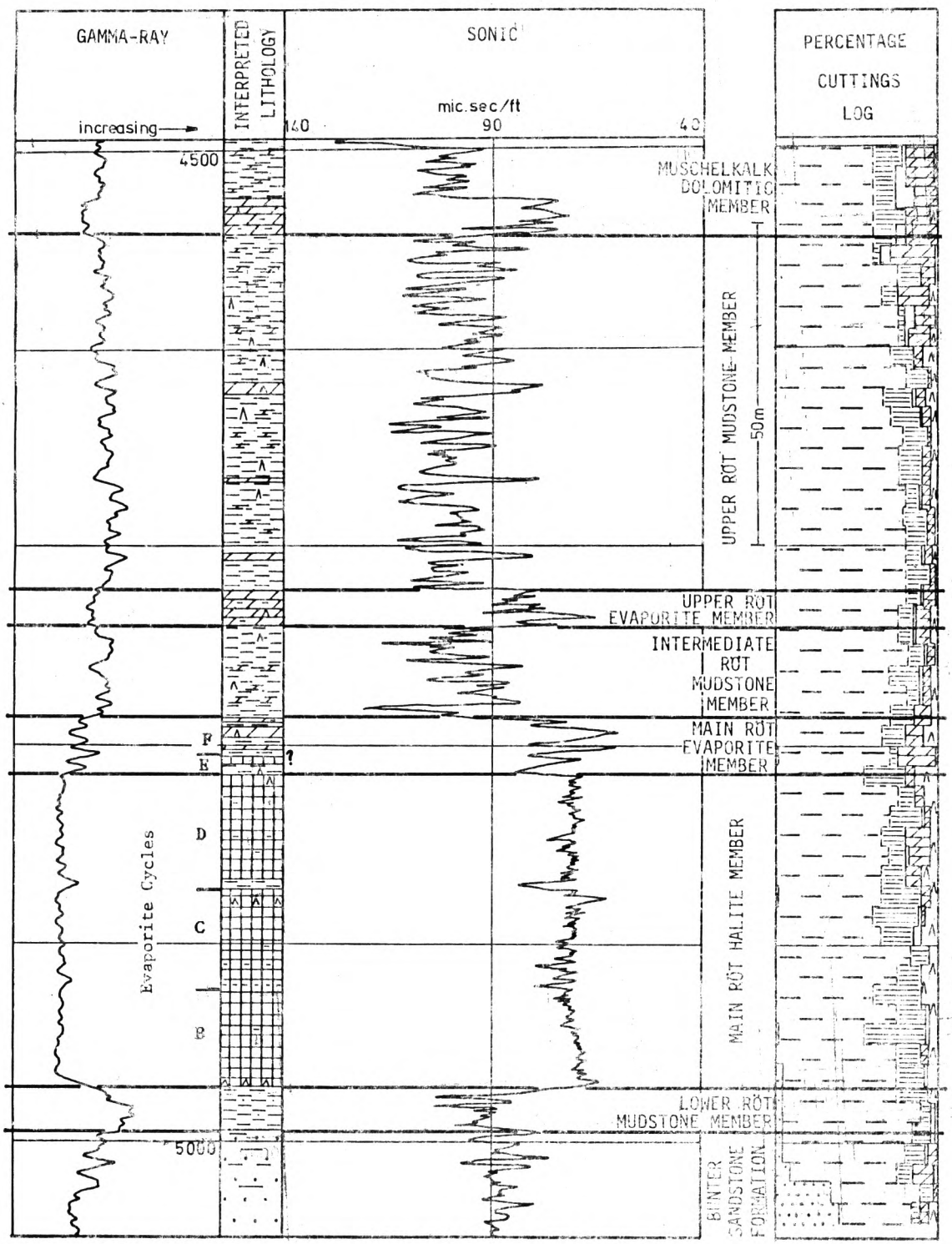
BUNTER SANDSTONE FORMATION

WELL48/6-2

WELL48/6-2

Scale 1:1000 (approx.)

Encl. Well H

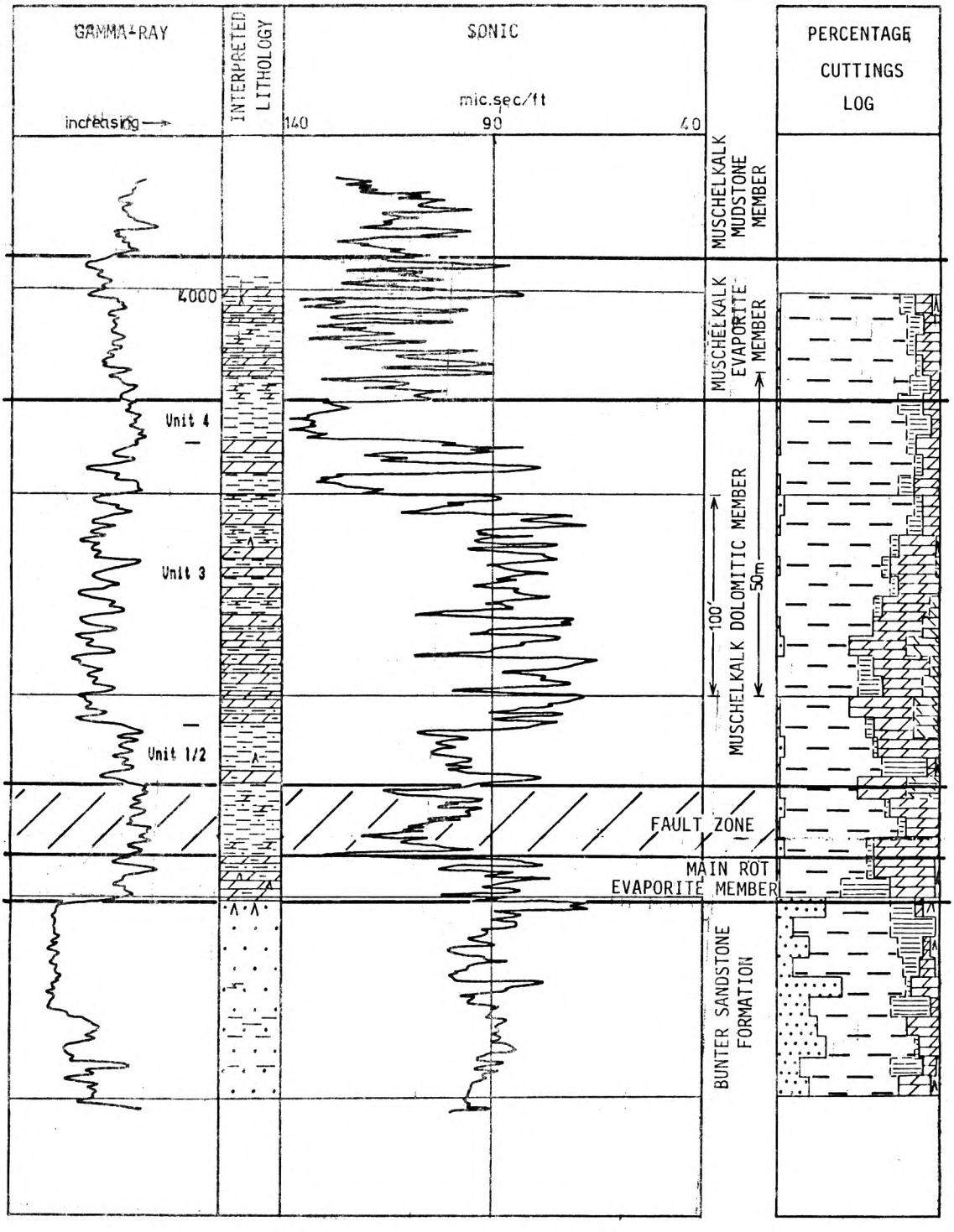


WELL 49/12-1

(LOWER PART)

Scale 1:1000 (approx.)

Encl. Well I

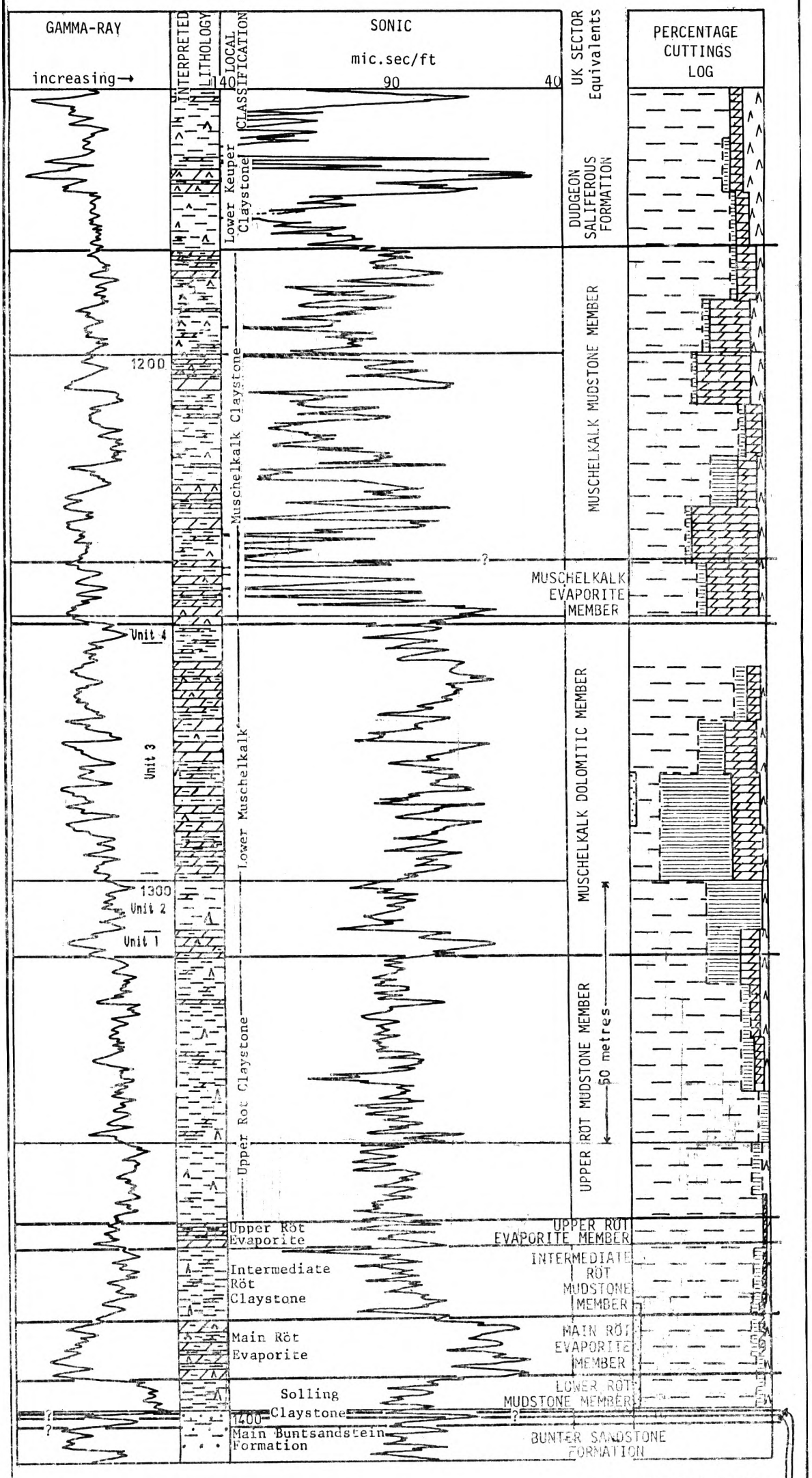


WELL 53/3-1

(LOWER PART)

Scale 1:1000 (approx.)

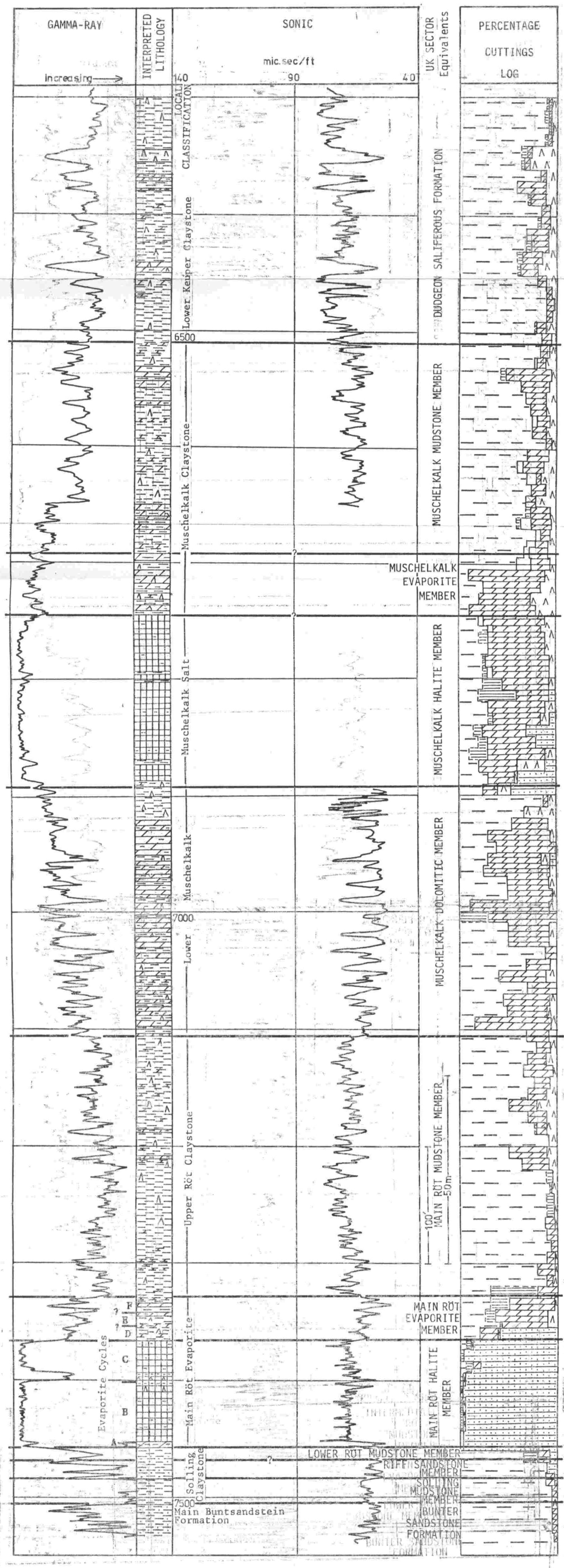
Encl. Well J



WELL K/13-1

Scale 1:1000 (approx.)

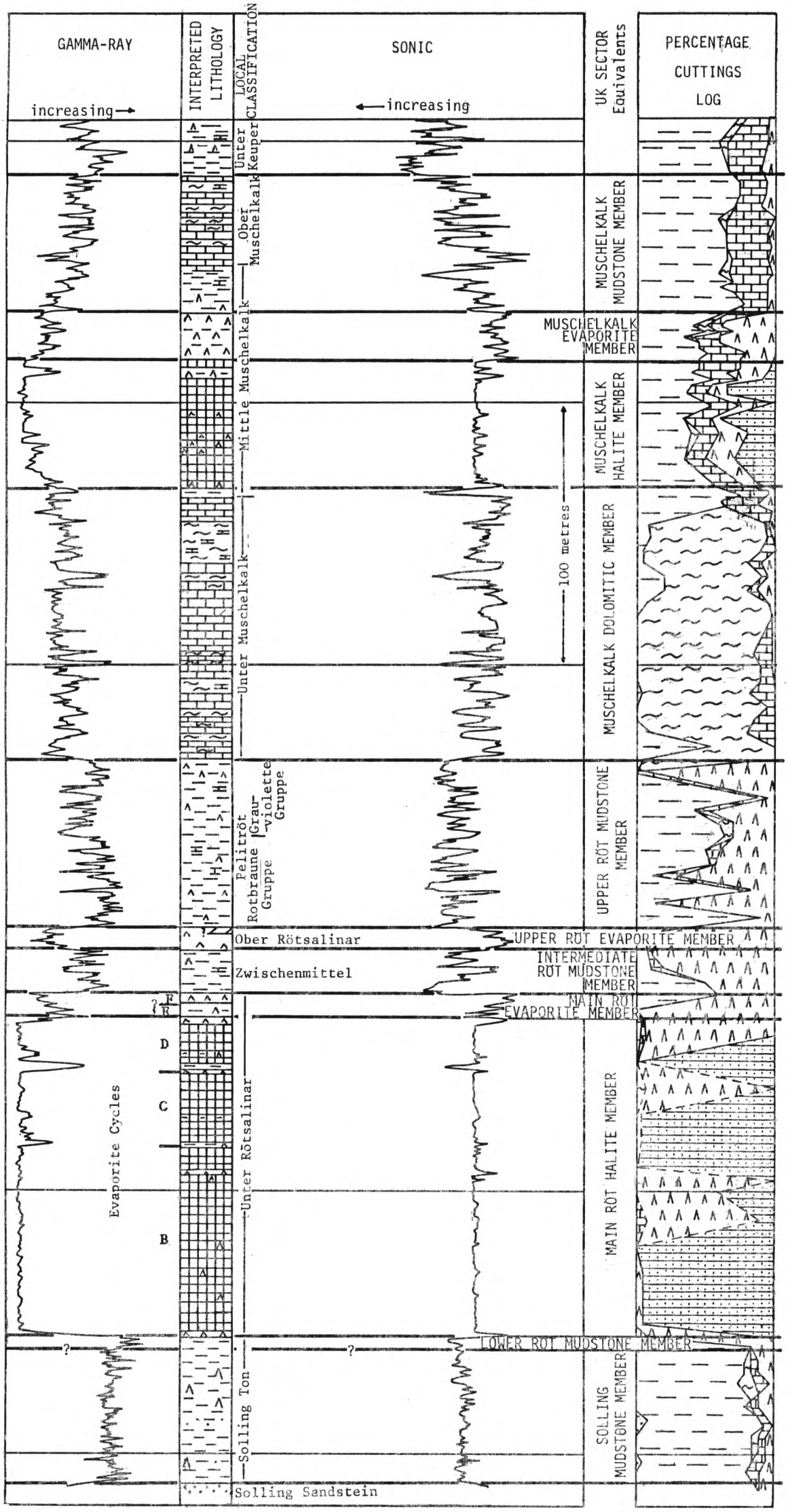
Encl. Well K



WELL Q/4-1

Scale 1:1000 (approx.)

Encl. Well L



WELL Ems River Mouth

Scale 1:2000 (approx.)

Encl. Well M

GAMMA-RAY

GAMMA-RAY

increasing →

INTERPRETED LITHOLOGY

LOCAL CLASSIFICATION

SONIC

← increasing

UK SECTOR Equivalents

PERCENTAGE CUTTINGS LOG

DUDGEON SALIFEROUS FORMATION

Unter Keuper

Ober Muschelkalk

MUSCHELKALK MUDSTONE MEMBER

?

MUSCHELKALK EVAPORITE MEMBER

Mittle Muschelkalk

MUSCHELKALK HALITE MEMBER

Unter Muschelkalk

100 metres

MUSCHELKALK DOLOMITIC MEMBER

UPPER RÖT MUDSTONE MEMBER

Pelitröt

Grauviolette Gruppe

Rotbraune Gruppe

Ober Rötsalinar

UPPER RÖT EVAPORITE MEMBER

Zwischenmittel

INTERMEDIATE RÖT MUDSTONE MEMBER

MAIN RÖT EVAPORITE MEMBER

F

E

D

C

B

Evaporite Cycles

Unter Rötsalinar

MAIN RÖT HALITE MEMBER

?

?

LOWER RÖT MUDSTONE MEMBER

Solling Ton

SOLLING MUDSTONE MEMBER

Solling Sandstein

WELL South Bremen

Scale 1:2000 (approx.)

Encl. Well N