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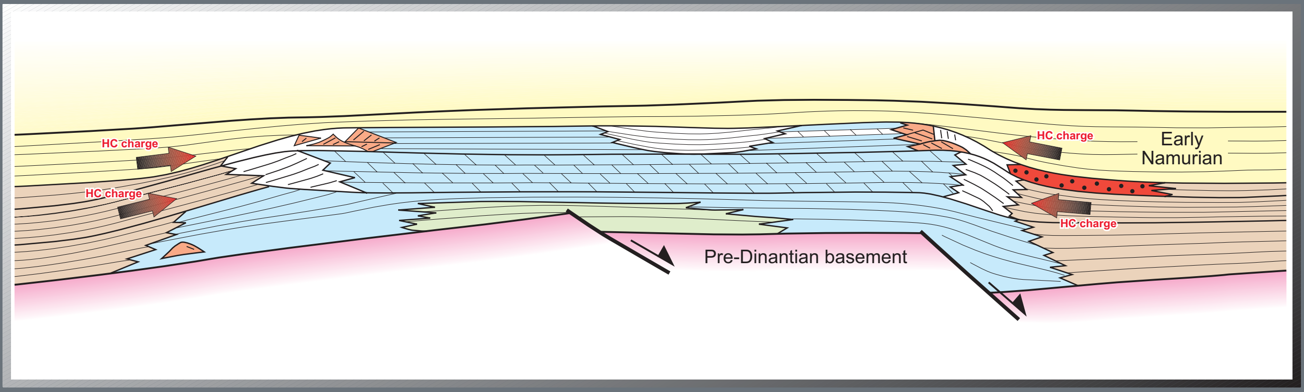

A Regional Review of the Dinantian Carbonate Play : Southern North Sea & Onshore UK

November 2007

A Report prepared for the UK DBERR
Total E&P UK

UK-REG-0278.FH

TOTAL E&P UK

A REGIONAL REVIEW OF THE DINANTIAN CARBONATE PLAY:

SOUTHERN NORTH SEA AND ONSHORE UK

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A report prepared for the UK DBERR.

Total E & P UK Limited, November 2007

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1 INTRODUCTION

1.1 Background

A regional cross-border hydrocarbon prospectivity overview covering parts of the UK, Netherlands, Belgium and Germany by Total E & P in 2002 highlighted the possibility of a poorly explored hydrocarbon play in the Dinantian (Lower Carboniferous). The main elements of this play include potential reservoir quality Dinantian carbonates charged from onlapping deep marine shales of the Early Namurian age (Figure 1.0). Top seal and lateral seal could also be formed by Early Namurian shales. Traps are likely to either structural e.g. tilted fault-blocks or stratigraphic e.g. carbonate build-up or stratigraphic pinch-out. Several large untested, structures are known to exist, for example the Winterton Lead in Quadrant 53 and 54. The main conclusion of this regional overview was that this Dinantian carbonate play is most favourably developed along the northern flank of the London-Brabant Massif (Figure 1.1).

The purpose of this report is to summarise much of the technical work undertaken by Total E & P on this play since the original overview of 2002 and to document this work in a report available to the UK DBERR which could be used in order to promote exploration for the play.

The study area trends NW – SE along the northern margin of the London-Brabant Massif extending from the UK/Netherlands median line in the SE to the central parts of the UK in the NW (Figure 1.1). It includes the East Midlands Shelf and the Hewett Shelf and surrounding basinal areas e.g. Sole Pit Trough, Widmerpool Gulf and Gainsborough Trough. However, as indicated on Figure 1.1, data outwith the study area from Belgium, Netherlands and onshore UK have been used in order to assess prospectivity.

The stratigraphic nomenclature used for the Carboniferous in this regional study is summarised on Figure 1.2.

1.2 Database

The main databases for the various evaluations comprise offshore and onshore well data. Dinantian well penetrations are highlighted on Figure 1.3 together with other useful deep, Carboniferous wells which provide important stratigraphical and lithological information and data. All well data used is in the public domain, much of which is old with only limited information available. Outcrop information from the UK and Belgium has also provided useful information, particularly on the stratigraphic nature of the Dinantian carbonates and their reservoir potential.

The main well data points are:

Onshore UK	**Offshore UK & Netherlands**	**Onshore Belgium & Germany**
Grove – 3	41/20-1	Heibaart -1 & 1bis
Milton Green -1	41/24a-1	Turnhout-1
Somerton 1	42/23-1	Poederlee -1
Croxteth -1	43/17-2	Geverik -1
Holme Chapel -1	44/29-1A	
Boulsworth -1	47/29a-1	
Plungar -1	48/22-1	
Duffield Borehole	53/12 -2 & 3	
Eakring 146	53/18-1	
Welton 1	P10-1, P16-1	
Strelley-1	O18-1	
Rempstone -1	S2-1 & 5, S5-1	
Wessenden-1		
Nettleham-2		
Nocton-1		

1.3 Exploration History

Within the UK Southern North Sea some 856 exploration and appraisal wells have been drilled to date resulting in the following discovered reserves:

Rotliegend play	8337Mboe
Triassic play	883Mboe
Carboniferous play	726Mboe

Offshore, exploration for the Carboniferous play has been restricted to the northern part of the Southern North Sea where Lower Permian evaporites of the Silverpit Formation form a caprock to the reservoirs provided by Upper Carboniferous deltaic sandstones (Figure 1.1). To the south of this area, this seal is lost as the evaporites of the Silverpit Formation are laterally replaced by sandstones of the Leman Sandstone Formation. As a result, over the bulk of the area, the main hydrocarbon play is the Leman Sandstone sealed by evaporates in the Upper Permian. Intra-Upper Carboniferous shales are generally too silty and fractured to form a viable seal for gas. Over much of the remainder of the Southern North Sea the Carboniferous has been generally the formation to provide the logging sump and consequently penetrations of the Carboniferous are often limited. To our knowledge no well has been drilled in the UK Southern North Sea to test the Dinantian Carbonate play, although large untested structures exist.

Some 280 exploration wells have drilled into the Carboniferous onshore UK and many (60%) have encountered hydrocarbon shows (Fraser, et al. 1990). Again, most have been for the Upper Carboniferous deltaic sandstone play, but, in contrast with the offshore domain, the main hydrocarbon type onshore is oil and consequently intra-Carboniferous shales provide a viable seal. Of these wells, many are old and poorly documented, and were not located on valid traps. Most of the valid tests are concentrated in the East Midlands, with as little as a dozen valid tests outside this area and none of commercial significance (Fraser, et al. 1990).

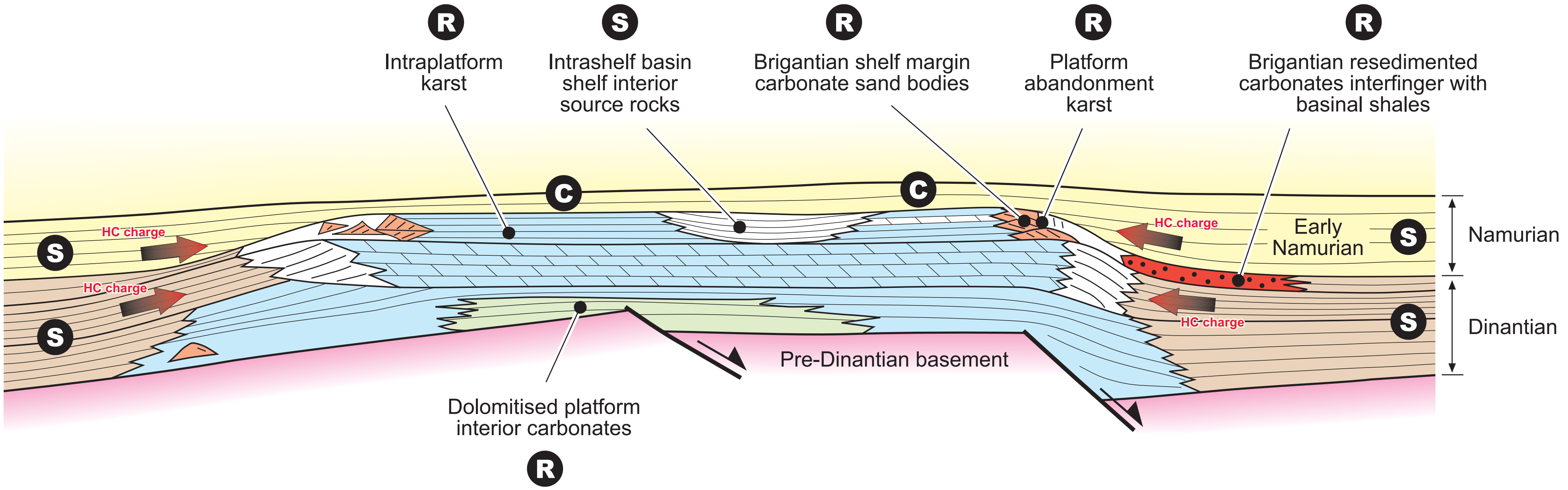
A review of available data suggests that there is currently no production from Dinantian carbonates in the area shown on Figure 1.1. The only historical production from the Dinantian carbonates was onshore UK at the following discoveries (Figure 1.4):

> **Eakring/Duke's Wood 1939**. Oil column extends into Dinantian with limited, local production of up to 50 tons/day.
>
> **Plungar 1953**. 3-7m column in the Dinantian limestone, minor production.
>
> **Nocton-2 1944**. Produced briefly from Dinantian limestone at 3 tons/day declining as water production increased.
>
> **Nettleham-1 1982.** Karstified top Dinantian carbonates which flowed at 12.9 bopd.
>
> **Hardstoft 1918.** A total of 26,000barrels was recovered over a 25 year period at a typical rate of 8-10 bopd.

From the available data it is unclear how many of the 280 well mentioned were designed to evaluate Dinantian carbonate plays, although it is thought that the number would be small. The more recent wells known to have targeted this play include Grove-3 (1981), Nettleham-1 (1982), Strelley-1 (1986) and Wessenden-1 (1987). The lack of success appears to be related to invalid traps due to seal failure caused by a sand-rich overlying Upper Carboniferous section or a lack of communication between the reservoir and source rock intervals.

Summary of Dinantian Hydrocarbon Systems Associated with Carbonate Platform

Schematic section illustrating Dinantian Carbonate petroleum system



S Source Rock	**R** Reservoir	**C** Cap Rock

Figure 1.0

TOTAL

Regional Review of the Dinantian Carbonate Play - Southern North Sea & Onshore U.K.

Location Map

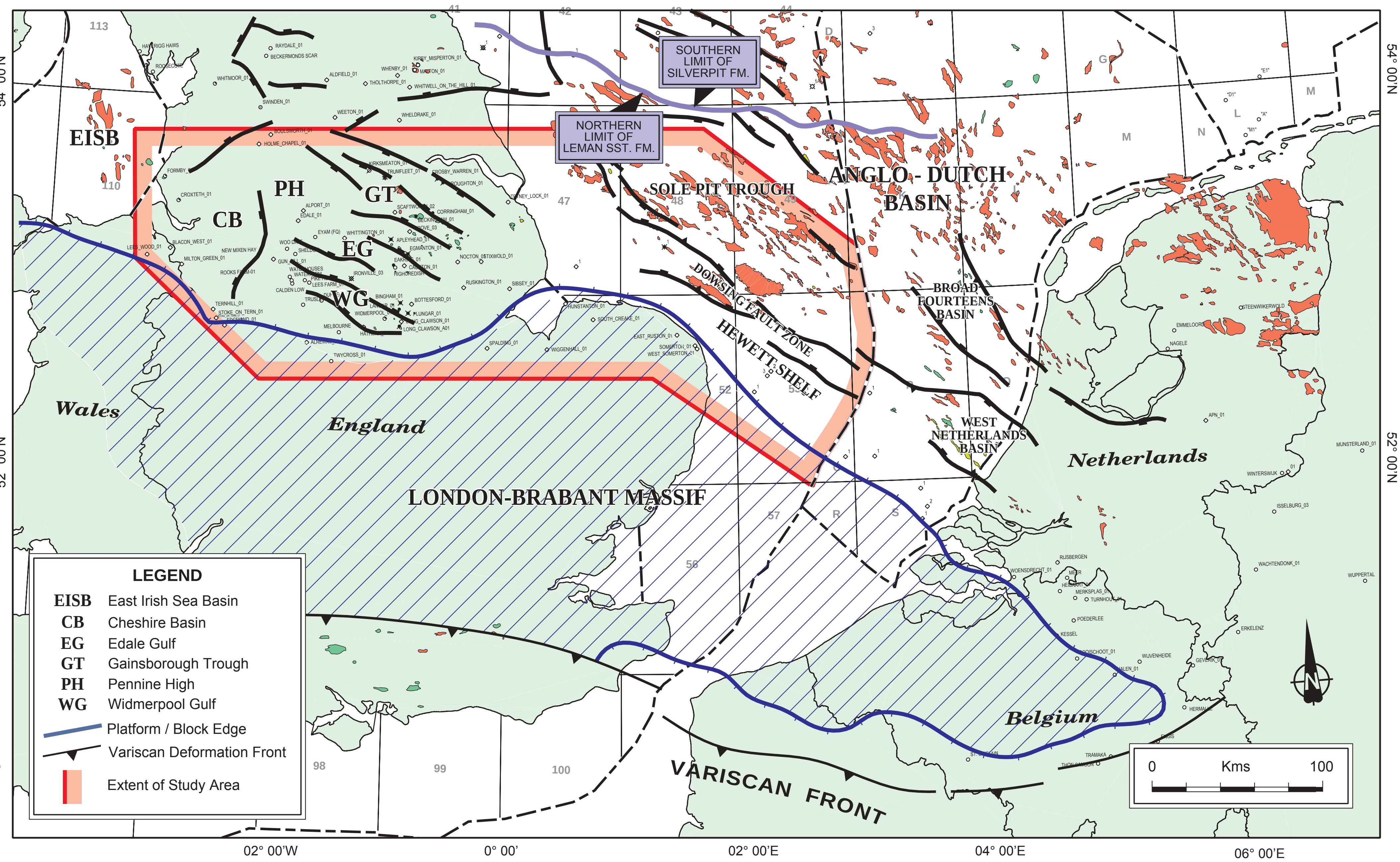


Figure 1.1

UK-REG-0286.dgn

17 August 2007

Carboniferous Stratigraphic Nomenclature

System	Sub System	Series		STAGES		AGE Ma
UPPER CARBONIFEROUS	SILESIAN			STEPHANIAN	C B A	300
		WESTPHALIAN		WESTPHALIAN D		
				WESTPHALIAN C		
				WESTPHALIAN B		311
				WESTPHALIAN A		
		NAMURIAN	C	YEADONIAN		315
			B	MARSDENIAN		
				KINDERCOUTIAN		
			A	ALPORTIAN		
				CHOKIERIAN		
				ARNSBERGIAN		
				PENDLEIAN		
LOWER CARBONIFEROUS	DINANTIAN	VISEAN		BRIGANTIAN		326
				ASBIAN		
				HOLKERIAN		335
				ARUNDIAN		
				CHADIAN		
		TOURNAISIAN		COURCEYAN		350
						360

Figure 1.2

Regional Review of the Dinantian Carbonate Play - Southern North Sea & Onshore U.K.

Study Area & Well Penetration Map

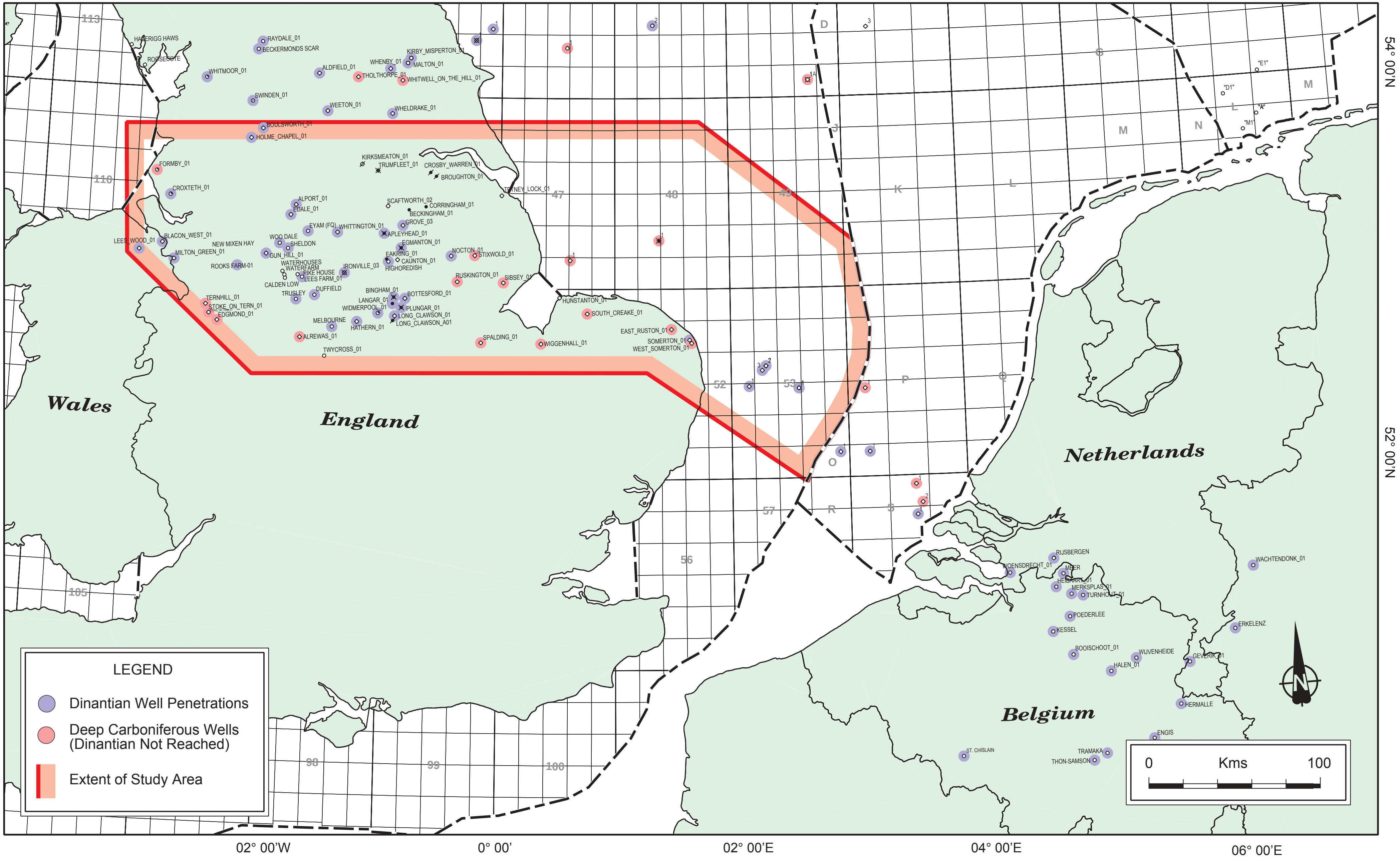


Figure 1.3

Regional Review of the Dinantian Carbonate Play - Southern North Sea & Onshore U.K.

Location of Dinantian Carbonate Discoveries

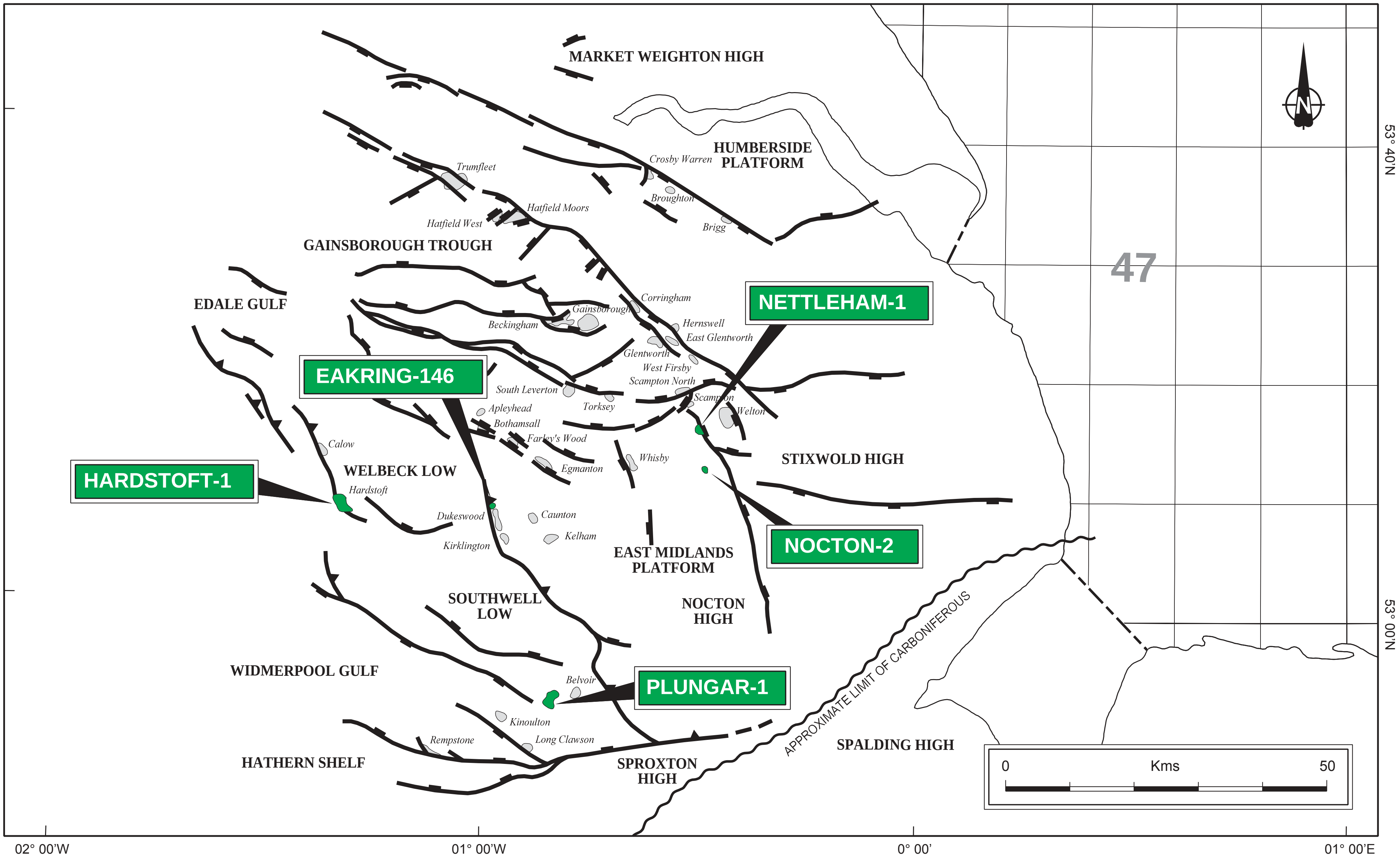


Figure 1.4

2 TECTONIC EVOLUTION

A generalised tectono-stratigraphic chart for the region is presented on Figure 2.0.

2.1 Introduction

The Caledonian Orogeny (446-441Ma) is considered to be the main plate tectonic event responsible for defining the deep structural grain of northwest Europe (Figure 2.1). It is widely recognised that the patterns of subsidence and inversion which emerged from late Palaeozoic times onwards were controlled by the underlying structure of the Caledonian basement. The main Caledonian tectonic provinces of the UK are illustrated on Figure 2.2.

Numerous publications and internal Total E & P regional seismic interpretations indicate that the predominant structural grain in the Anglo-Dutch Basin and central parts of the UK is NW-SE and this was almost certainly inherited from the Caledonian Orogeny. This trend of faulting appears to have been re-activated during the Carboniferous, Mesozoic and Tertiary controlling phases of both extension and compression.

2.2 Early Devonian Extension

The Caledonian Orogeny was closely followed by the onset of an extensional tectonic regime in the early Devonian which initiated rift basins such as the Midland Valley and the Northumberland Basin, which are located onshore UK but outside the study area. Many of these Devonian basins formed through the reactivation of earlier Caledonian fabrics and thus have similar strike and dip directions to the underlying Caledonian thrust faults. Structural anisotropies e.g. thrust faults and major folds in the basement are the predominant control on the subsequent orientation of later sedimentary basins and deformational structures in the overlying cover sequence. It is these Caledonian fabrics which influenced the orientation of the early Devonian rift basins, some of which would go on to develop further in the Early Carboniferous.

2.3 Late Devonian – Early Carboniferous Crustal Extension

Various tectonic models exist to attempt to explain the driving mechanism behind early Carboniferous N-S orientated crustal extension in NW Europe. Leeder (1976) attributes the rifting to back-arc extension resulting from subduction related rollback of the Rheic oceanic crust beneath the Armorican microcraton. The result of which is a failed back-arc rift basin in northern England. Several authors (e.g. Coward 1993; Maynard *et al.* 1997 etc) prefer a model invoking crustal escape tectonics caused by the initiation of the Acadian orogeny in North America as an alternative cause of crustal extension.

Whatever the mechanism, the result of early Carboniferous extension was the development of a series of extensional grabens and half-grabens and intervening platform areas to the north of the London-Brabant Massif in a belt extending from Belgium through the Southern North Sea and into onshore UK and Ireland (Figure 2.3). The trends of these features were controlled by the deep Caledonian fault systems. For example, in the central parts of the UK are the NW-SE trending Widmerpool Gulf and Gainsborough Trough. This structural trend also continues throughout the Anglo-Dutch Basin where, for example, the major NW-SE trending Sole Pit Trough is thought to be underlain by a Dinantian graben system. This is seperated from the Hewett Shelf (Dinantian platform area) by the NW-SE trending Dowsing Fault Zone (Figure 2.3).

There was pulsed rifting during the Dinantian which was interspersed by quieter, stable tectonic periods. The main periods of rifting and basin formation were:

Courceyan
Late Chadian to Late Holkerian
Late Asbian to Early Brigantian

During the Mid Brigantian a compressive tectonic event resulted in the formation of the Sudetic or Brigantian Unconformity.

2.4 Variscan Deformation

In contrast with the underlying Dinantian, the Namurian to Westphalian section represents a post-rift, thermal sag phase with sedimentation gradually burying the underlying rift topography such that the study area was covered by major deltaic systems during the Westphalian.

The Variscan Orogeny which occurred towards the end of the Carboniferous was a result of continental collision of Gondwana with Laurentia to the west and Iberia to the south to form the super continent of Pangaea. The effects of this orogeny on the study area commenced in late Westphalian C times and continued until the end of the Carboniferous. The major effect of this compression was the inversion and erosion of the pre-existing Dinantian basins (Figure 2.4). In contrast, the platform areas remained relatively undeformed with a preserved section of younger Westphalian to Stephanian rocks.

2.5 Triassic - Jurassic Tectonic Evolution

By late Permian times a new tectonic regime had become established in northwest Europe. Widespread regional thermal subsidence following Variscan collision led to the development of the southern Permian basin in the region of the southern North Sea.

A renewed phase of rifting also occurred during the Triassic and Jurassic re-activating many of the basins in the offshore environment e.g. Sole Pit Trough, West Netherlands and Broad Fourteens Basins. In contrast, much of central England remained tectonically quiescent being situated on the rift shoulder of the Anglo-Dutch Basin and avoided large scale tectonic movements. Major Late Jurassic to Earliest Cretaceous transtensional movement, possibly associated with regional thermal uplift, resulted in the widespread Cimmerian Unconformity with locally severe erosion.

2.6 Cretaceous-Tertiary Tectonic Evolution

The offshore basins in the Southern North Sea tend to show a two stage post-Jurassic phase of inversion and erosion. The first being in the Late Cretaceous (Turonian – Coniacian) and resulted in progressive thinning and then onlap of the Chalk onto the areas formed by the inverted underlying basin e.g. Sole Pit Trough. This was followed by either non-deposition or erosion of the early Tertiary sequences during the Miocene.

In contrast the basins of Central England do not show these phases of inversion. However, uplift of the Central Pennine High during the Early Tertairy imparted an easterly dip of 1° to 3° on the Mesozoic and older rocks together with significant erosion.

From the above, it can be seen the tectono-stratigraghic development of this area is complex and controlled by several phases of rifting and compression which vary from one location to another. The result of this is that the hydrocarbon charge model for any prospect or lead needs to be assessed individually rather than relying on broad regional comments.

Simplified Tectono - Stratigraphic Chart for Study Area

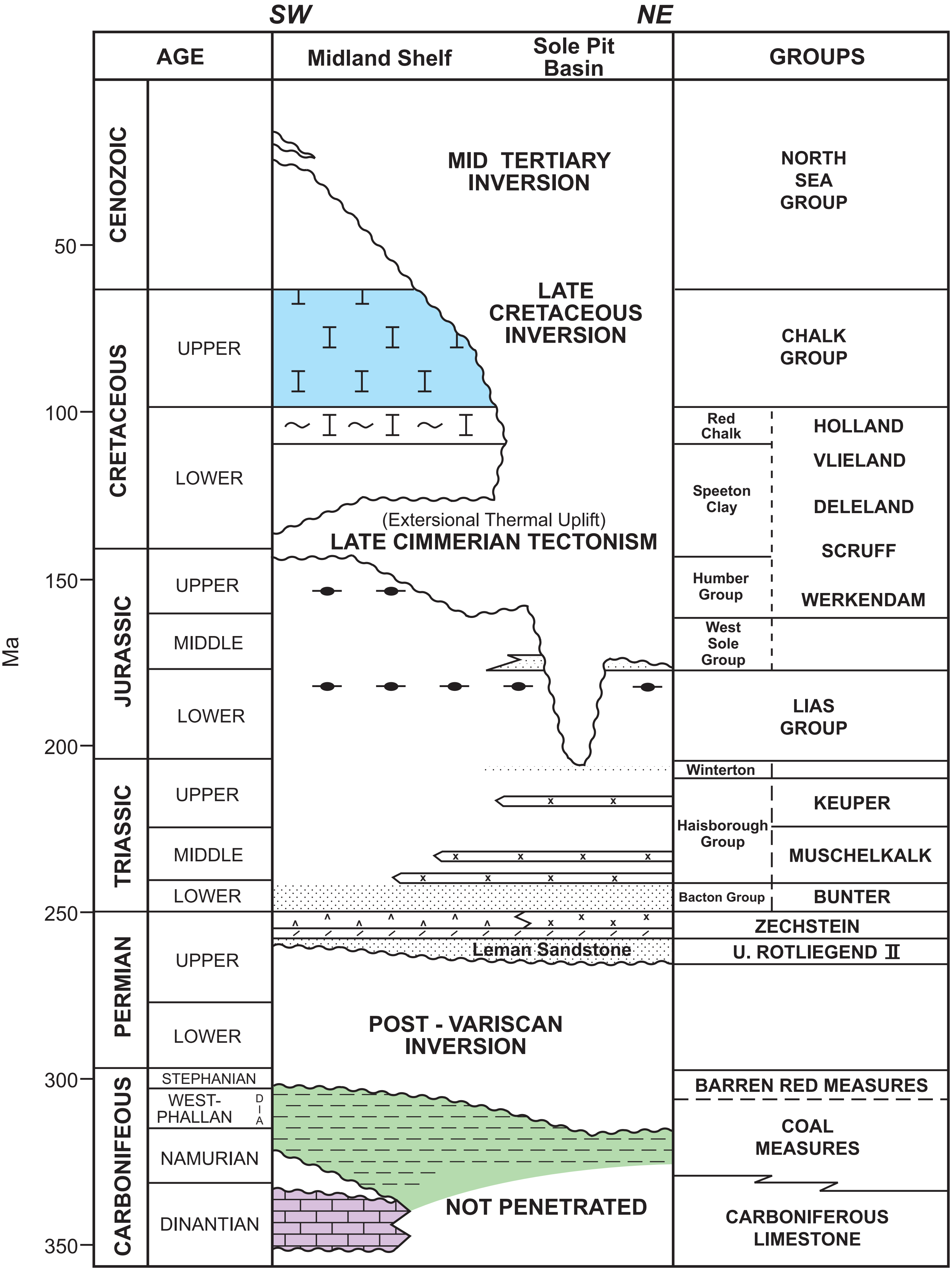
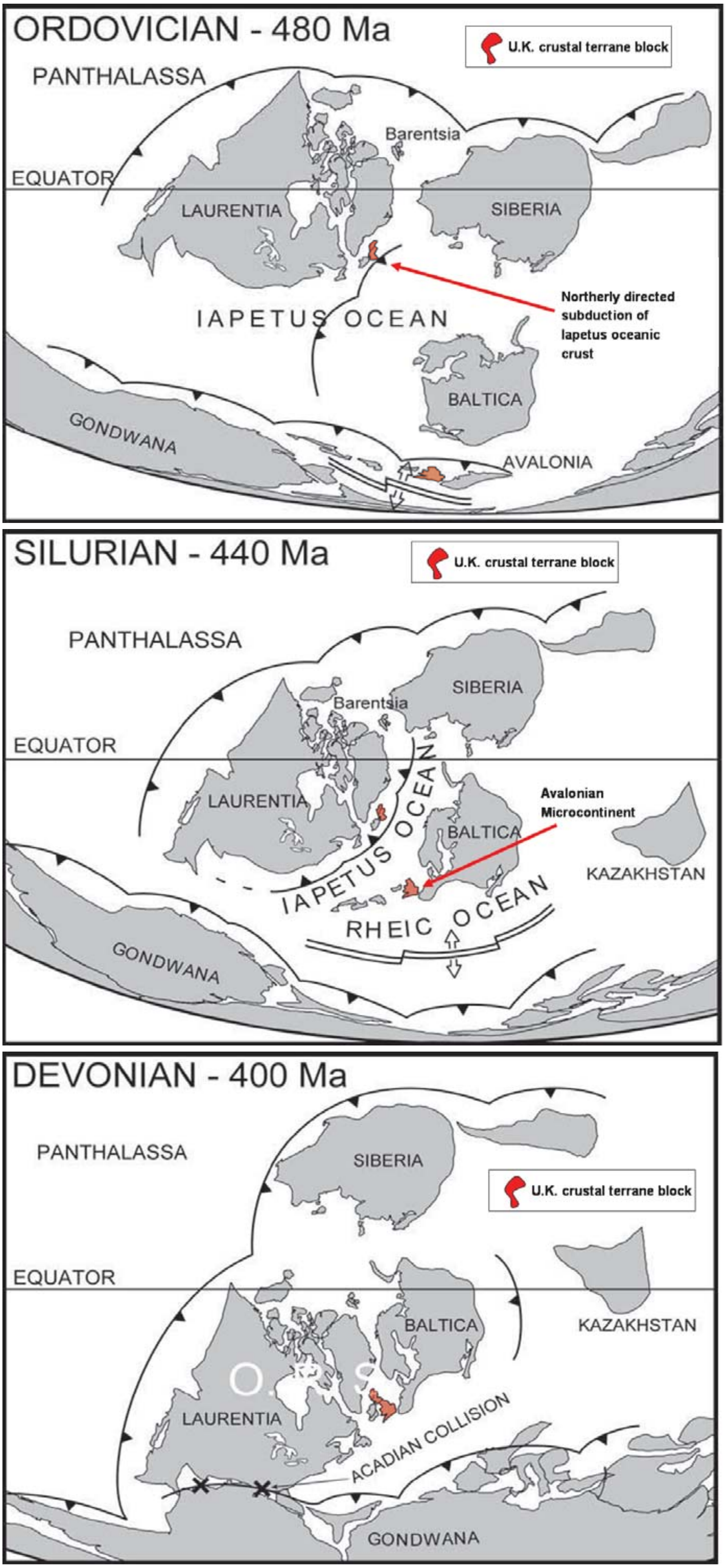


Figure 2.0

Global Reconstructions Leading to Caledonian Orogeny

Origin modified from :
http://www.scotese.com



Northerly directed subduction of Iapetus oceanic crust

Avalonian Microcontinent

Figure 2.1

Caledonian Tectonic Provinces of England & Wales

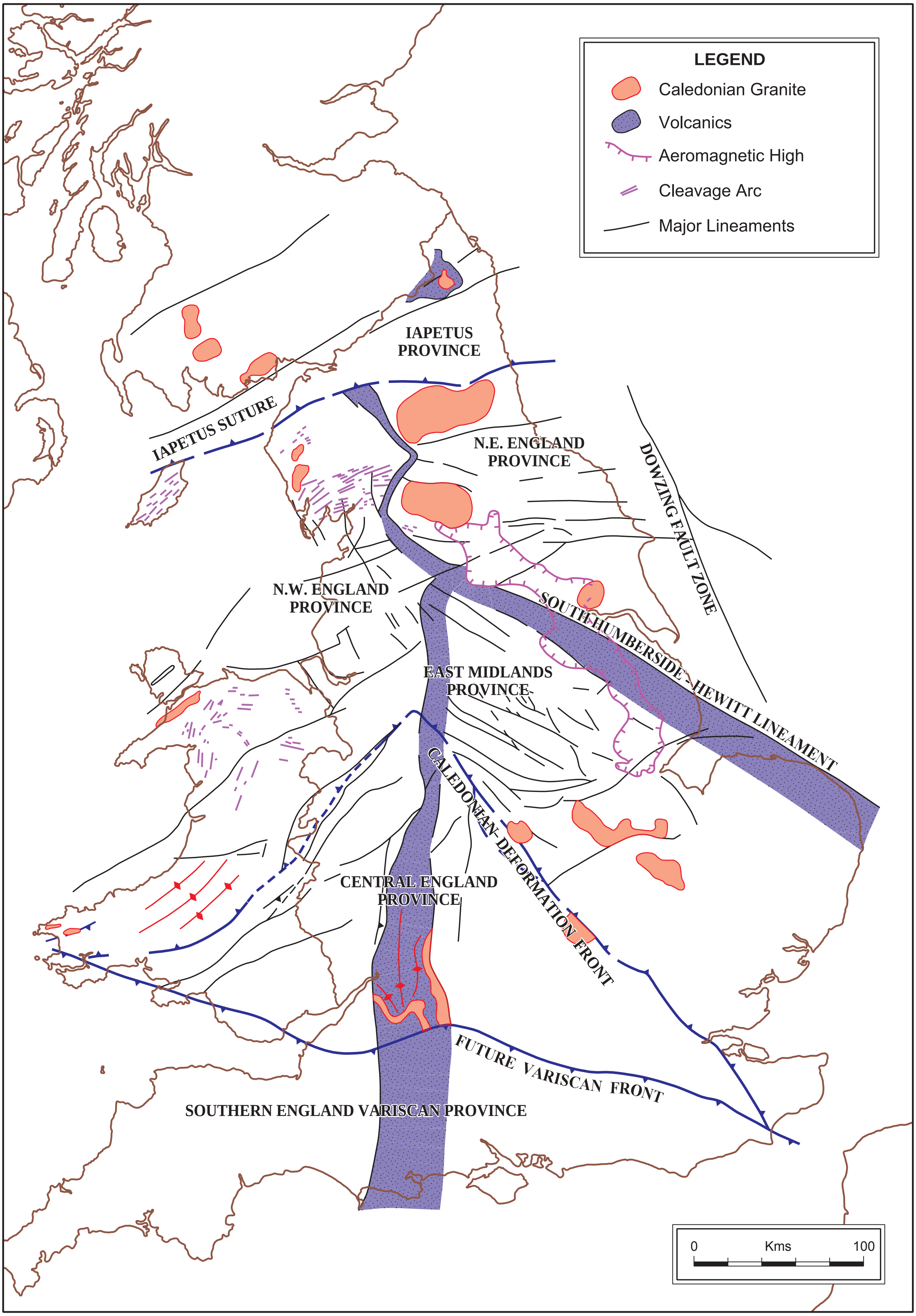


Figure 2.2

Regional Review of the Dinantian Carbonate Play - Southern North Sea & Onshore U.K.

Basin Platform Topography Resulting from Early Carboniferous Rifting

After Glennie 1998

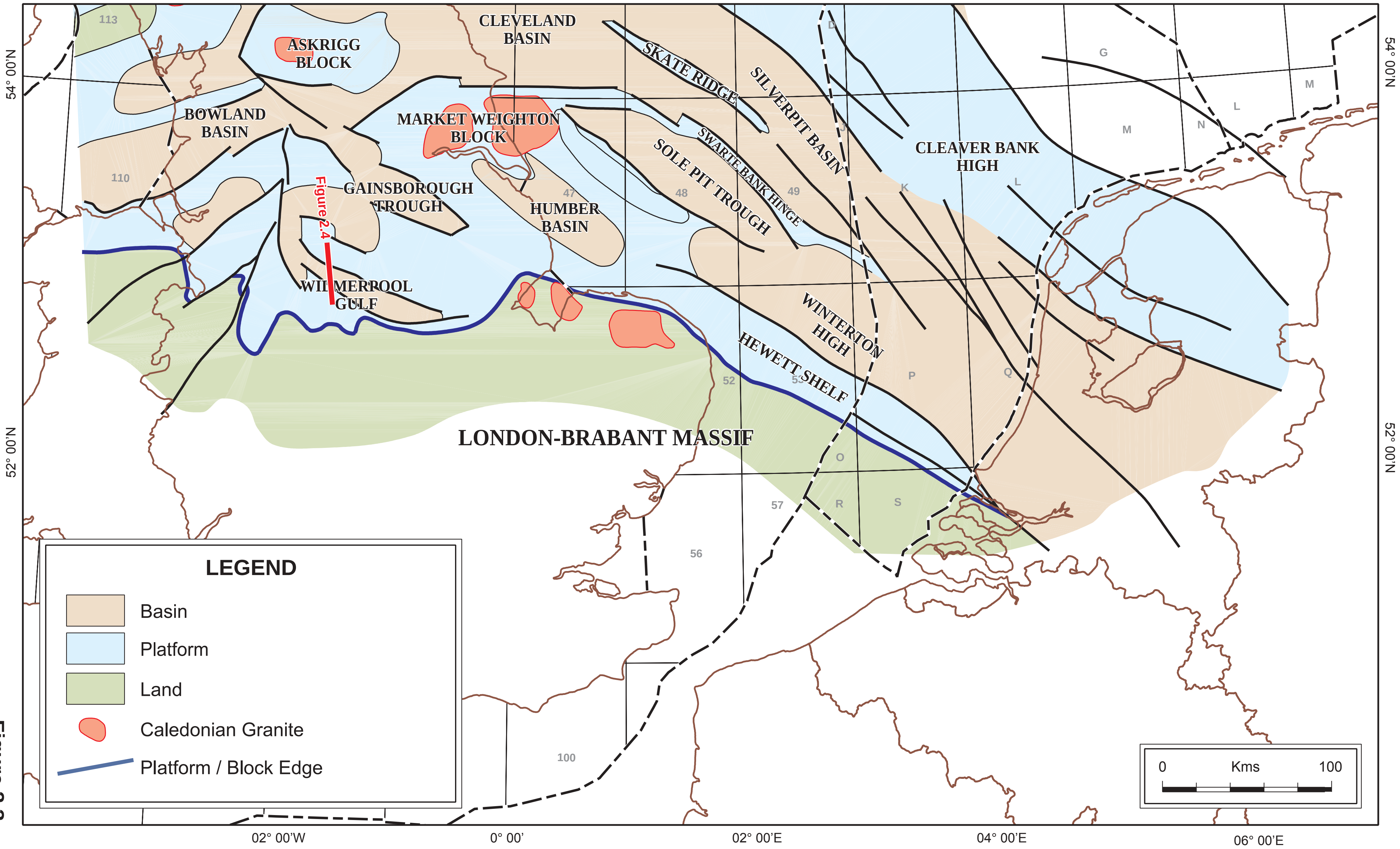


Figure 2.3

S - N Seismic Line & Geological Cross-section across the Widmerpool Gulf

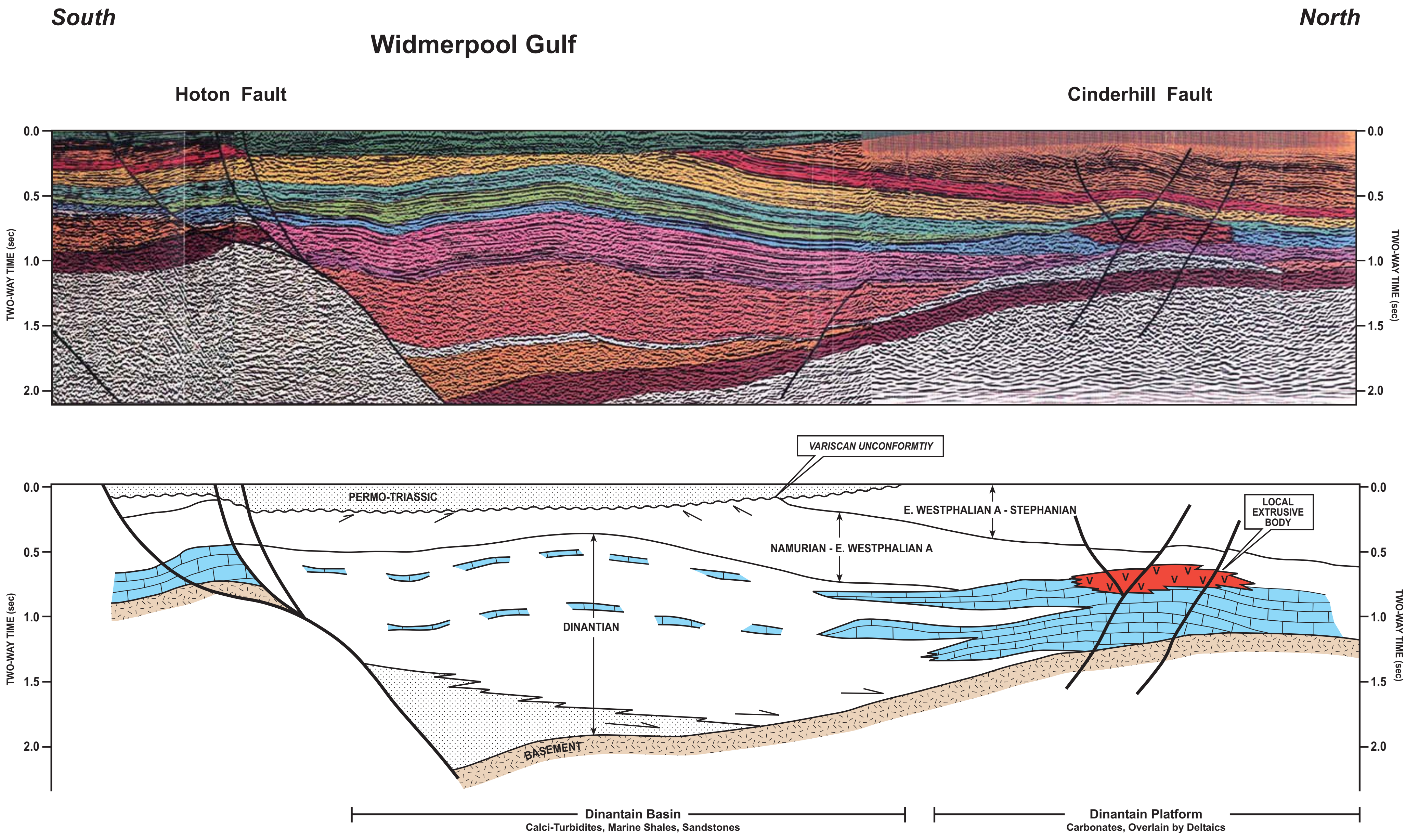


Figure 2.4

Location : See Figure 2.3

Adapted from Fraser et al, 1990

3 CARBONIFEROUS STRATIGRAPHY

3.1 Dinantian

The stratigraphy and facies distribution of the Dinantian, particularly in the offshore regions, is poorly constrained due to the lack of deep well penetrations. The schematic Dinantian palaeogeography illustrated on Figure 3.0 is based on available well data, published articles and internal Total E & P reports. Broadly, during the Dinantian, the area to the north of the London-Brabant Massif comprised either shallow water carbonate deposition over the structural highs or deep-marine mudstones and calci-turbidites in the intervening basins. Sediment input from the London-Brabant Massif was minimal and the basins were largely starved of sediment supply. However, further north, as indicated on Figure 3.0 major deltas were prograding southwards burying the underlying rift topography and at the same time terminating carbonate deposition. This deltaic system continued to prograde southwards eventually terminating all carbonate deposition by the end of the Dinantian.

In 2006 a proprietary log based sequence stratigraphic framework for the Dinantian was established for Total E & P based on well data from the UK, Netherlands and Belgium (Figure 3.1). Where possible, this has been constrained by biostratigraphic data. Six sedimentary sequences are identified, each of which represents a 3rd order sequence and these are summarised on Table 3.1.

The Tournaisian to Arundian (S1 – S3) sequences are interpreted as a series of off-lapping carbonate ramps units that onlap the emergent basement. Each sequence consists of a basal mixed siliciclastic-carbonate marginal marine sequence passing up into a progradational ramp. Sequences separated by sequence boundaries are often karstified. Outcrop evidence from the UK and Belgium indicates that in the deeper water parts of the carbonate ramp setting Waulsortian mud mounds occur and these are generally of Chadian to Arundian in age. These build-ups range from isolated mounds a few tens of metres high, to complexes hundreds of metres high that cover several square kilometres. In general, these build-ups are not reefal frameworks and they comprise micrite with low permeability and vuggy porosity. Being situated in a more seaward location they are less susceptible to karstification processes. Well data show that the Tournaisian to Arundian carbonates are often dolomitised and proprietary Total E & P studies suggest that dolomitisation results from fluids derived from connate waters expelled from compacting mudstone sequences.

The Holkerian (S4) represents the start of the transition from carbonate ramp systems fringing areas of exposed basement to the development of carbonate platform systems with rimmed margins. The carbonate systems became differentiated into carbonate shelves and basins. Basement highs were finally covered by carbonate deposition thereby cutting off the local supply of siliciclastic sediment. This sequence often shows a distinct electric-log character, consisting of a high gamma maximum flooding surface overlain by a relatively thick aggradational HST (high stand systems tract) that comprises a lower, low gamma interval and an upper, higher gamma interval.

Sequence 5 (Asbian) marks the first fully developed rimmed carbonate shelf systems nucleated over basement highs and fringing the margins of the London-Brabant Massif. These carbonate shelves were surrounded by deep-marine basins in which distal carbonate turbidites and deep-marine mudstones were deposited (Figure 3.2). Outcrop evidence from Northern England shows that the Asbian shelf carbonates consist of shallowing-upward glacio-eustatic carbonate shelf cycles (Walkden 1987, Horbury 1989). The cycles consist of argillaceous subtidal bioclastic limestones deposited during transgressions with high energy packstones and grainstones representing late TST (transgressive systems tract) to TST deposits. These cycles are capped by calcrete and karstic surfaces overlain by K bentonites that represent volcanic ash deposits modified by soil processes (Figure 3.3).

Sequence 6 (Brigantian) also comprises a number of glacio-eustatic shallowing-upwards carbonate shelf cycles with palaeosols and palaeokarst at sequence boundaries. Potential reservoirs occur at the carbonate platform margins with the development of grainstone carbonate bodies and re-sedimented carbonates in base of slope setting. The Brigantian is often eroded at the carbonate platform margins with the development of a karstic surface at the top of the carbonate platform.

3.2 Namurian

The generalised gross depositional environment of the Namurian across the region is illustrated on Figure 3.4.

Post rift subsidence at the end of the Dinantian led to the drowning of the carbonate platforms and the cessation of carbonate deposition. Outcrop and well data indicate that during the Early Namurian the area immediately to the north of the London-Brabant Massif was characterized by the deposition of pro-delta organic-rich shales. These shales typically show a high gamma and low sonic electric log response, This interval is thickest in the deeper parts of the basins and gradually thins and onlaps the surrounding carbonate platforms. Black organic-rich shales are known to occur immediately to the north of the London Brabant Massif in a connected belt extending from Belgium through the UK and into the Dublin Basin in Ireland. Although there is a lack of deep well control in the Sole Pit Trough, seismic data suggests that there is a thick Namurian section onlapping the Hewett Shelf which could contain organic rich shales. The nearest two offshore wells supporting this concept are 43/17-2 and 48/3-3 both of which encountered high gamma mudstones at the base of the Namurian.

During the middle part of the Namurian (Arnsbergian to Alportian) course siliciclastics gradually infilled the basins in the north of England in response to major southerly prograding delta systems. Whilst the more southerly basins are characterised by contemporaneous distal pro-delta mudstones.

By Kinderscoutian times much of the underlying rift topography had been buried beneath the advancing delta systems resulting in widespread shallow-water and delta top conditions. Much of the Namurian is characterised by high frequency cyclicity, comprising goniatite-bearing marine mudstones passing upwards into channel sandstones and delta top deposits associated with colas and palaeosols. Typically, these shallow-water delta cycles are 10m to 50m thick and each cycle is characterised by a major fluvial sandbody. It is generally accepted that these cycles result from high frequency glacio-eustatic sea-level changes. The goniatite-bearing marine mudstones (marine bands) reflect maximum flooding surface condensed sections and the overlying delta front to delta top succession, progradation of a HST.

3.3 Westphalian – Stephanian

The generalised gross depositional environment of the Westphalian across the region is illustrated on Figure 3.5.

The early Westphalian A section includes distributary channels and shallow fresh-brackish lakes that were infilled by lacustrine deltas, crevasse splays and overbank deposits. The upper part of the Westphalian is characterised by coal swamps and meandering fluvial channels.

During the mid-late Westphalian C times a major phase of basin inversion commenced to the north of the London-Brabant Massif radically changing the sedimentary depocentres and facies patterns across the region. The sediments derived from the inverted and eroded areas are often referred to as the Barren Red Measures or Barren Red Beds. These red-coloured rocks are thought to represent alluvial fan complexes with medium to coarse grained fluvial sandstones, overbank silts and clays, and lateritic palaeosols. However, the base Permian unconformity cuts across the late Carboniferous stratigraphy of the region and much of the evidence for the deposition of the sediments has been removed by erosion.

Age and Sequence	Log Character	Environment
S6: Brigantian; 4/5th order glacio-eustatic cycles.	**Shelf:** cyclic, moderate gamma carbonates with gamma spikes. **Slope:** spikey gamma. **Basin:** high gamma.	**Shelf:** low energy cyclic subtidal shelf carbonates with karst at cycle boundaries. **Slope:** carbonate boulder beds and shale **Basin:** shales with carbonate turbidites.
S5: Asbian; 4/5th order glacio-eustatic cycles.	**Shelf:** cyclic with clean carbonates and gamma spikes, high gamma palaeosols. **Slope:** spikey gamma. **Basin:** high gamma.	**Shelf**: cyclic subtidal shelf carbonates with karst and palaeosols at cycle boundaries. Grainstones near shelf margins. **Slope:** local boulder beds of shelf carbonates interbedded with shales. **Basin:** shale and carbonate turbidites.
S4: Holkerian; a single 3rd order sequence. Local erosion at top.	High gamma TST and MFS, low gamma TST/early HST, higher gamma late HST.	**Shelf:** Low energy non-rimmed carbonate shelf with peritidal shelf interior facies. **Basin:** deep to mid carbonate ramp.
S3: Arundian; at least 5 4th order sequences that onlap basement and earlier cycles.	Aggradational TST with maximum flooding interval, progradational HST.	Basal mixed siliciclastic-carbonate marginal marine sequence then progradational carbonate ramp. Sequences separated by sequence boundaries. Carbonates are often dolomitised.
S2: Chadian to Arundian; at least two 4th order sequences that onlap basement and earlier sequences.	Aggradational TST with maximum flooding interval, progradational HST.	Fluvial, marginal marine and near shore siliciclastics and carbonates, rare evaporites. Carbonates often dolomitised.
S1: Tournaisian to Chadian; at least one 4th order cycle that onlaps basement.	Aggradational TST with maximum flooding interval, progradational HST.	Fluvial, marginal marine and near shore siliciclastics and carbonates. Carbonates often dolomitised.

Table 3.1 Dinantian Sequence Stratigraphy

Regional Review of the Dinantian Carbonate Play - Southern North Sea & Onshore U.K.

Schematic Dinantian Palaeogeography

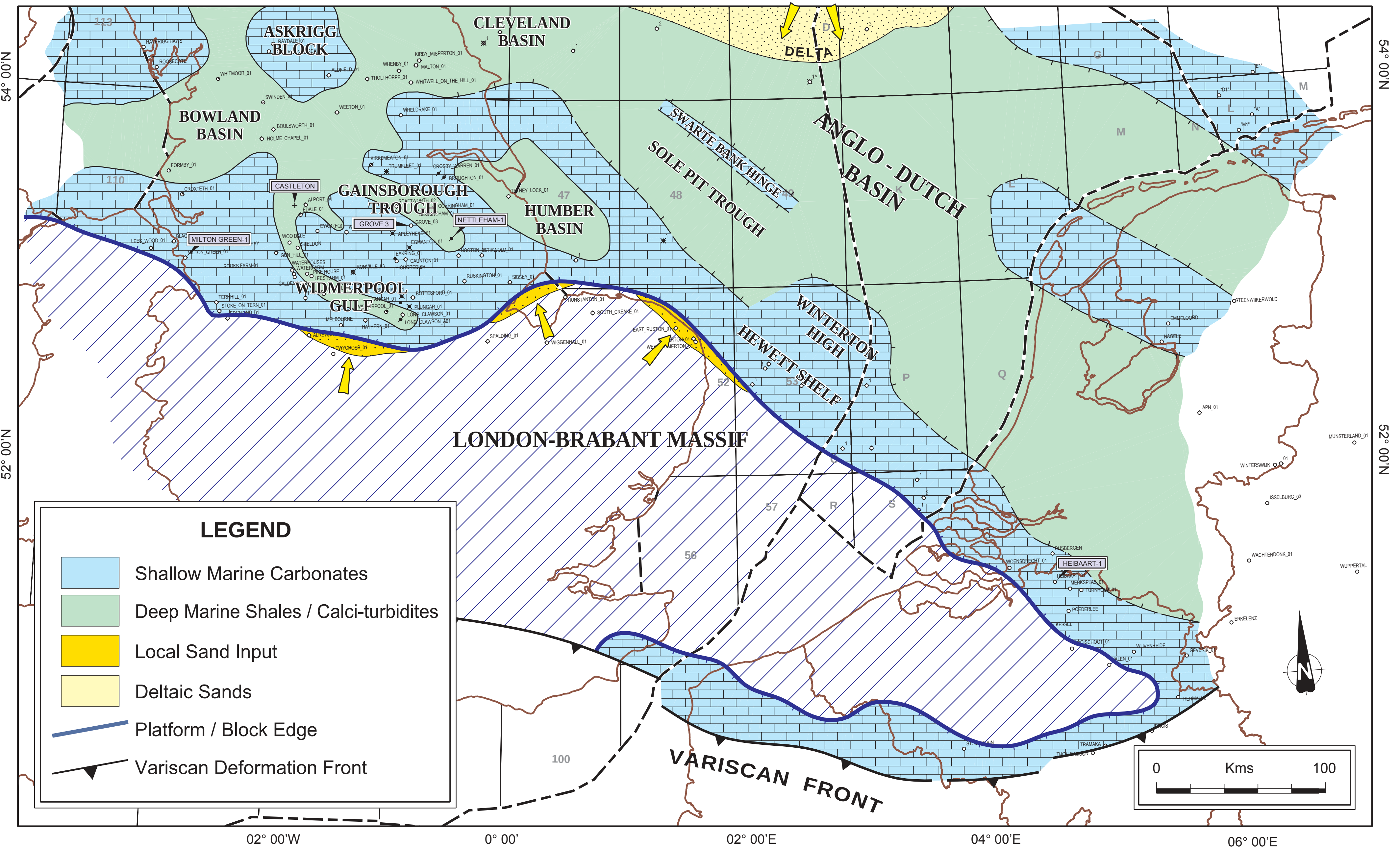
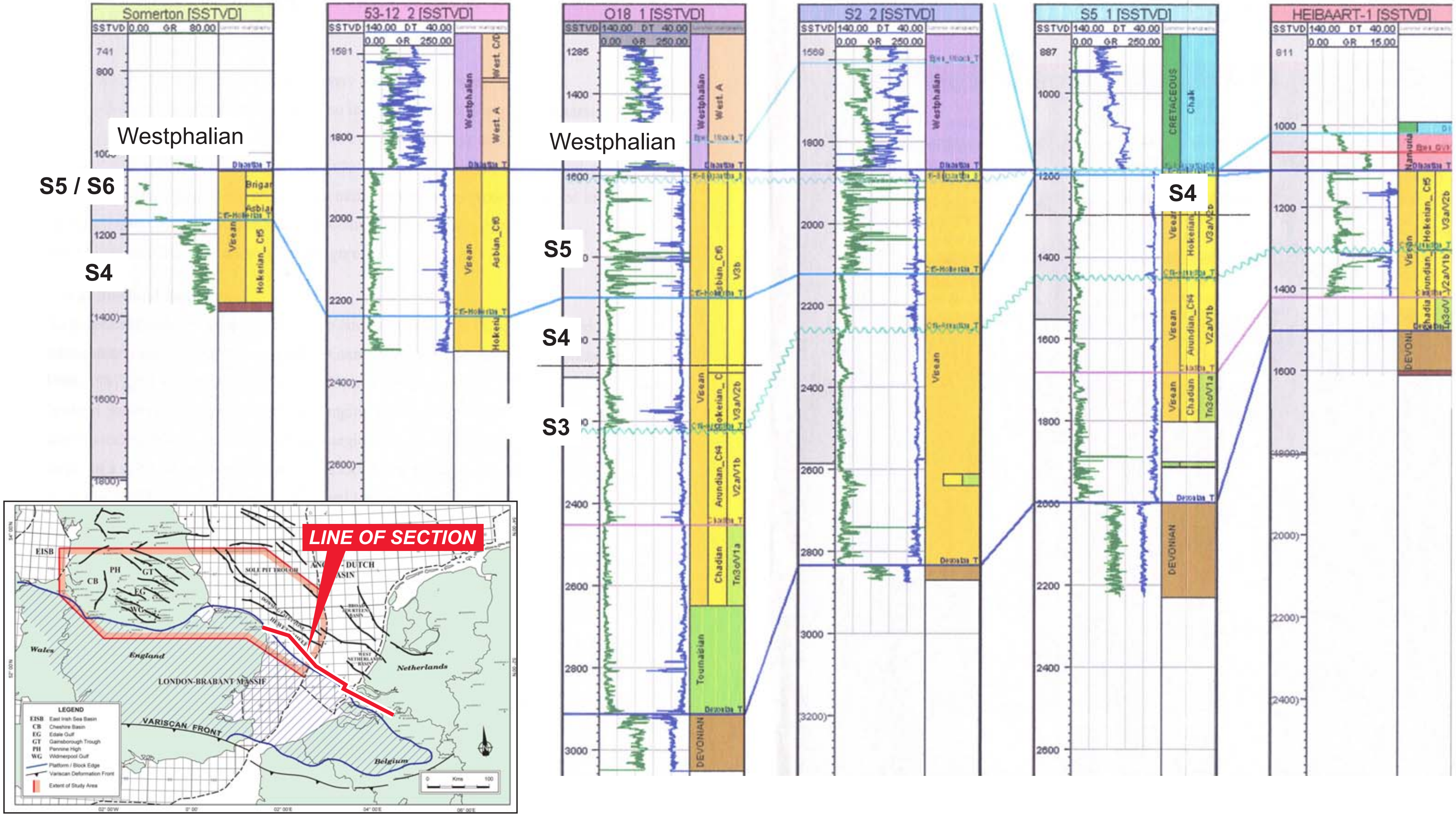


Figure 3.0

Regional Review of the Dinantian Carbonate Play - Southern North Sea & Onshore UK

Sequence Stratigraphic Correlation of the Dinantian



Location Map

Figure 3.1

U.K.C.S. - Southern North Sea

Schematic Section Illustrating Dinantian Platform/Basin Facies

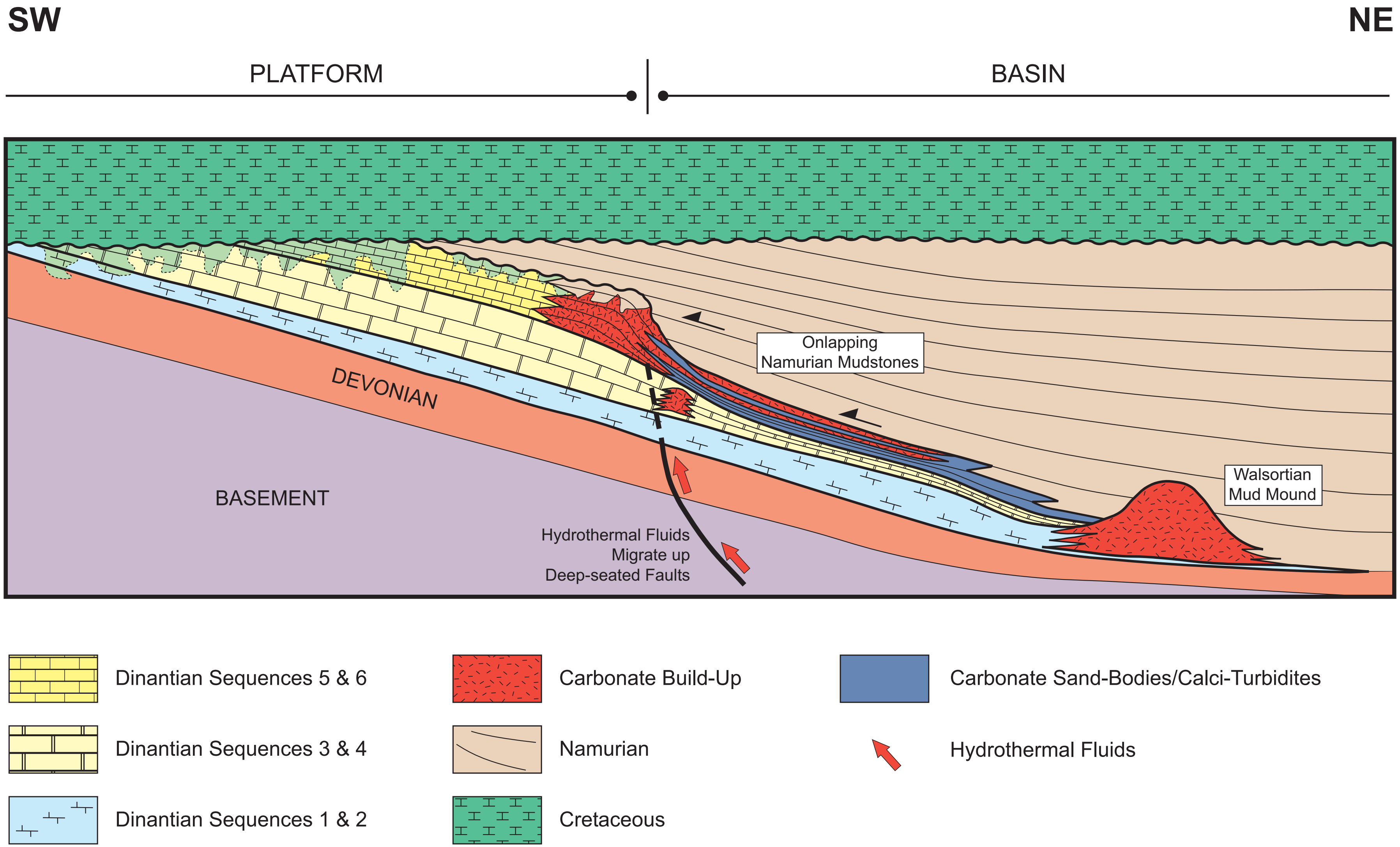
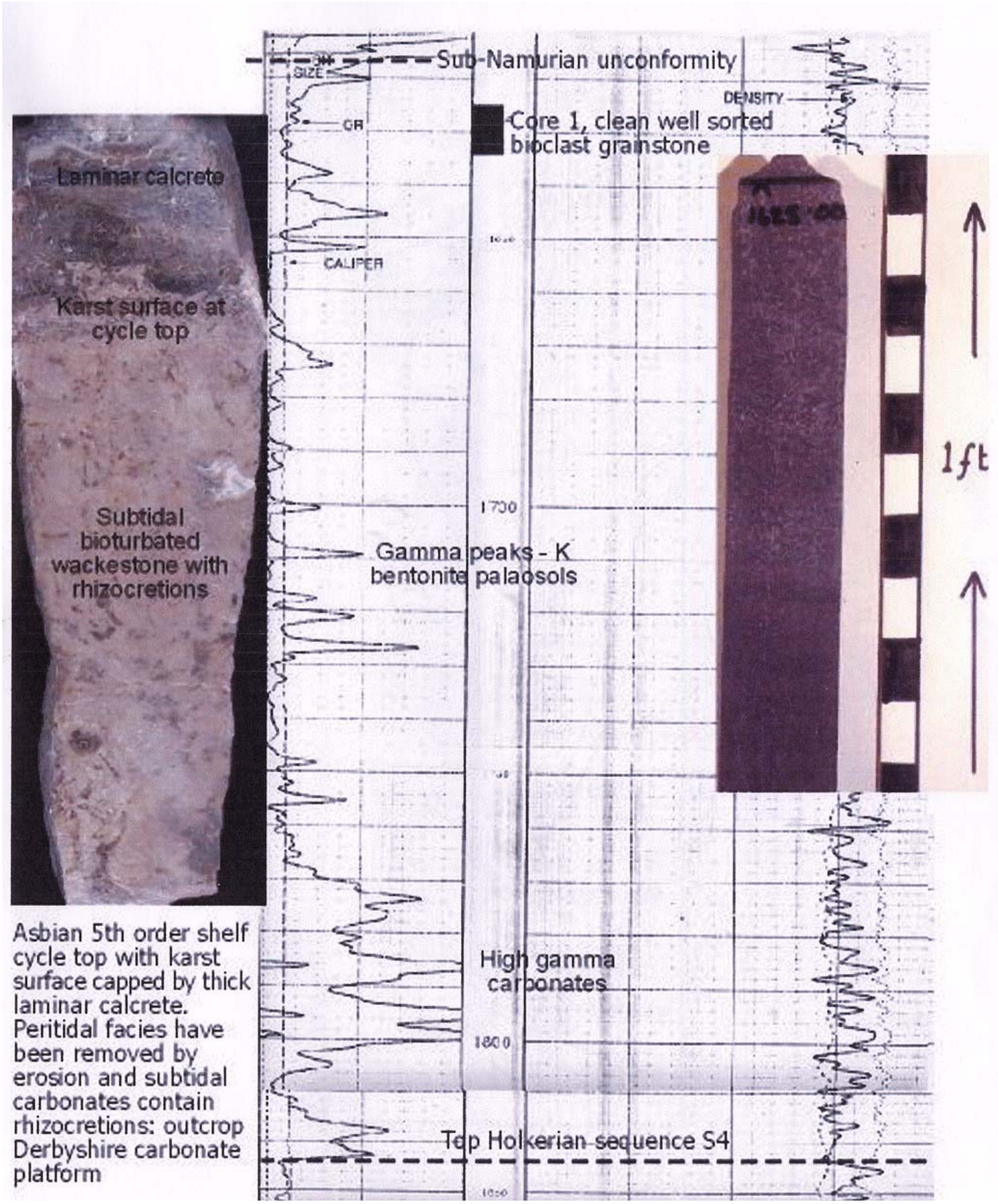


Figure 3.2

High Gamma Asbian Shelf Carbonates:
Early Asbian Cyclic Shelf Carbonates Wessenden-1



Asbian 5th order shelf cycle top with karst surface capped by thick laminar calcrete. Peritidal facies have been removed by erosion and subtidal carbonates contain rhizocretions: outcrop Derbyshire carbonate platform

Figure 3.3

Regional Review of the Dinantian Carbonate Play - Southern North Sea & Onshore U.K.

Schematic Early Namurian Palaeogeography

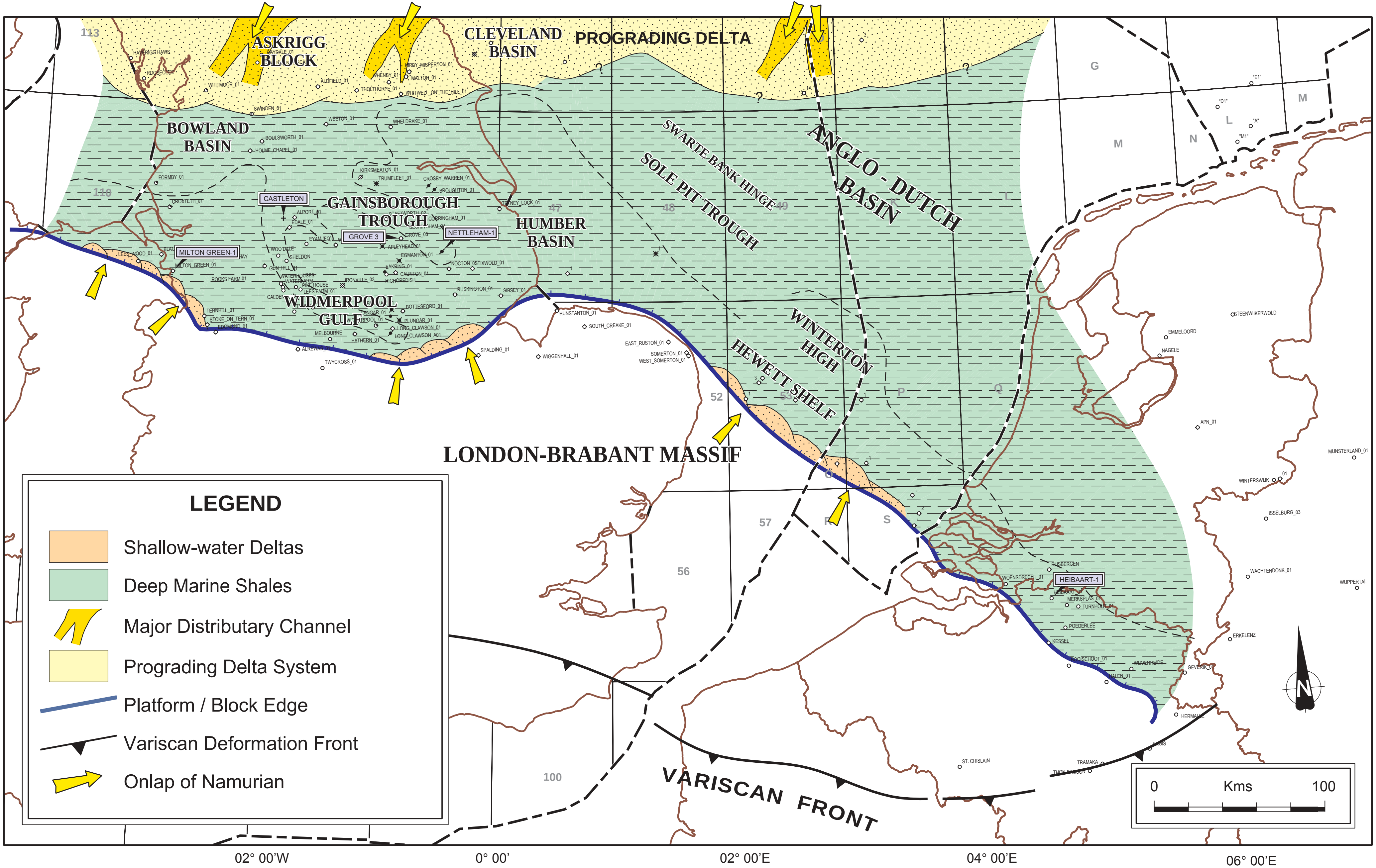


Figure 3.4

Regional Review of the Dinantian Carbonate Play - Southern North Sea & Onshore U.K.

Schematic Westphalian Palaeogeography

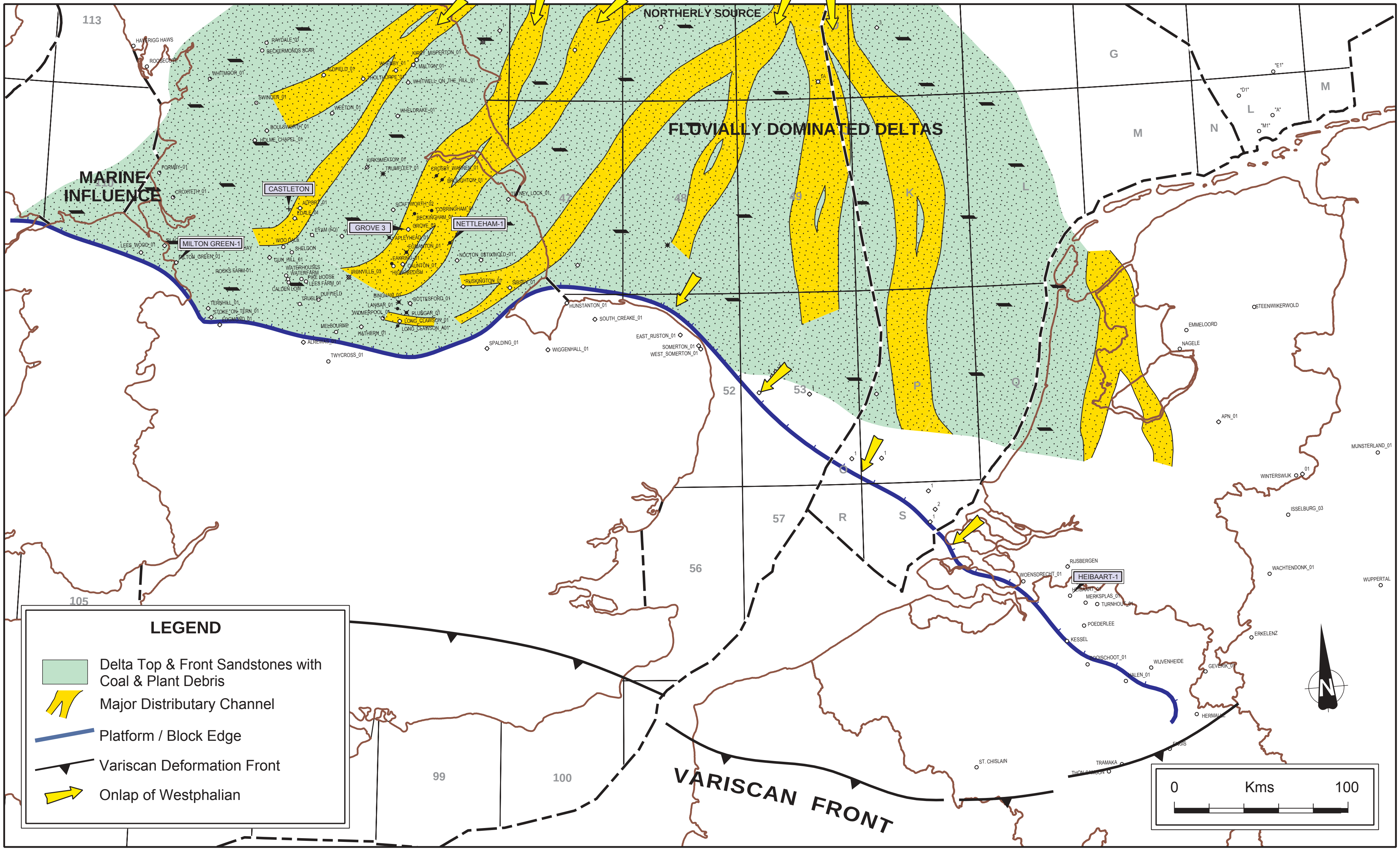


Figure 3.5

4 RESERVOIR DEVELOPMENT

4.1 Introduction

An assessment of the reservoir quality of the Dinantian carbonates is hampered by the lack of core data and modern data collection techniques. Most onshore and offshore wells to have penetrated the Dinantian are more than 20 years old and only continued into the Dinantian for stratigraphic information or to provide a logging sump. Consequently, the data available from these wells is limited and inconsistent. Although onshore wells Grove-3, Holme Chapel-1, Wessenden-1, Strelley-1 and Nettleham -1 appear to have targeted this play it is unclear whether they were located on valid traps.

This assessment of reservoir potential is based on outcrop information from the UK and Belgium, much of which is summarised on Figure 4.0. In addition, a proprietary study for Total E & P UK examined the cores and electric log data from the wells tabulated below:

Well	Core	Log suite
UK		
Boulsworth-1	X	
Eakring-146	X	
Grove-3	X	X
Holme Chapel-1		X
Rempstone-1	X	X
Roddlesworth-1	X	X
Somerton-1	X	X
Strelley-1		X
Welton-1	X	X
Wessenden-1	X	X
53/12-2		X
Netherlands/Belgium		
O18-1	X	X
S5-01	X	X
S2-02	X	X
Heibaart		X

Typically, the matrix porosity of Dinantian carbonates is very poor, ranging between 1% and 5% (Figure 4.1). The poor matrix porosity is a result of burial and compaction of lime-muds in the absence of skeletal framework reef-building organisms which became established later in the Carboniferous. Consequently the development of reservoir quality carbonates depends on secondary processes such **karstification, fracturing** and **dolomitisation**. The main macropore types found in the Dinantian include karst cavities and open fractures of tectonic origin, both of which were difficult to detect from the available electric logs. Consequently, where core data are absent, the following criteria were used to identify possible cavities and fractures:

	Karst System	Fractures
Mud Loss	High volume treated by LCM, often associated with log anomalies	Low volume, not necessarily associated with a log anomaly
Drilling behaviour	Bit drops and positive drilling breaks over an interval	
Electric log anomalies	Wide hole/high porosity indications. Chaotic dips. Gamma spikes may indicate karst fill. Karst fill, palaeosols and mudstones may also be recognised by a high gamma	Wide hole/high porosity at a point or multiple points

For example, the sequence boundaries at the top of the Arundian sequences in Wessenden -1 show caliper, sonic and density/porosity anomalies associated with mud losses. These are interpreted as evidence of karstic exposure associated with emergence at the sequence boundary at the tops of these cycles. The log data also suggests that the karst occurs as enlarged fractures or vuggy cavities at discrete intervals below the sequence boundary. Examples of mud loss in the Arundian sequence not associated with log anomalies are interpreted as open fractures.

Karstification is a well established global process which can result in the development of significant reservoir quality. Two examples of where this has occurred are the Cambro-Ordovician carbonates of the Xanglin Field in China and the Late Cretaceous carbonates of the Lacq Field in southern France. The general organisation of the karstic voids is illustrated on Figure 4.1. In the Vadose Zone (up to 100m high) the vertical circulation of groundwater has created a generally vertical network of voids, whilst in the underlying Phreatic Zone (can be over 200m high) circulation is horizontal producing a horizontal network of caverns and vugs.

It is possible to classify karst reservoirs according to their stratigraphic hierarchy (Figure 4.2) into three categories as follows:

High frequency cycle scale 5th Order (up to 10KY) (Figure 4.3)
High frequency composite sequence scale 3/4th Order (10KY – 2MY) (Figure 4.4)
Supersequence 2nd Order (1 – 30MY)

As indicated on Figure 4.2 it is karst development associated with a supersequence 2nd order cycle that is likely to lead to the development of significant reservoir quality. This is generally associated with major sea level drops and the generation significant sequence boundaries, for example, at the top of the Brigantian, Asbian, Arundian and Chadian. In contrast, the 4/5th order cycles glacio-eustatic cycles developed in the Brigantian and Asbian (see section 3.1) are unlikely to be associated with significant reservoir enhancement (Figures 4.3 and 4.4). In all three categories mentioned above karstification appears to be most prominent at the shelf edge and this is often referred to as coastal karst.

4.2 Evidence of reservoir development – from wells.

4.2.1 Heibaart-Leonhout Underground Gas Storage.

In Belgium, deep meteoric karst developed on positive topography e.g. crest of tilted fault-blocks. Once such example in Belgium is the Heibaart-Leonhout structure developed on the footwall of a major fault system separating the Dinantian basin and platform terrains. On such topographic highs, preferential dissolution of the massive carbonates (build-ups) occurs generating large scale caverns (metric size) and conduits. Local karstic collapse breccia with a possible association with deep evaporite collapse breccia may also linked to this process. Unfortunately, such karsts have been filled by shales during the Namurian transgression and are generally sealed.

The well Heibaart-1 (Belgium)(Figure 4.5 and 4.6) and the other wells drilled on the Heibaart-Leonhout structure encountered good reservoir characteristics in the Dinantian carbonates. This reservoir is today used as gas storage by Distrigaz (Belgium). Significant mud losses and consequent bit drops were encountered while drilling the Heibaart-1 well, which provide evidence for the presence of karstic features in the well bore. This well was later lost and a sidetrack was performed, Heibaart-1bis, and cores were cut. The core study showed that only the algal-microbial mounds exhibit macroscopic karst features. No karstic features have been recognised in the inter-mound facies which consist of open platform facies dominated by packstone texture. Enlargement of pre-existing karstic features and more recently formed fractures/fissures show partial filling or lining by pyrite, quartz, zinc and lead. This phase of karst enhancement strongly suggests that circulating hydrothermal fluids were responsible for the leaching and dissolution of pre-existing karstic features.

The reservoir characteristics of the matrix are again very poor with porosities of 1-3% and permeability extremely poor. The effective porosity is created by the karstification which provides an enhanced effective permeability of between 40-50mD, locally up to open vugs and caverns. The upper part of the carbonate build-up is the most karstified with good connectivity via breccias, fractures and dissolution vugs and caverns. A second karstified unit is developed 100m deeper and together form 120m of net pay within the 200m of structural closure. These two reservoir zones are developed throughout the 20km² of the Heibaart-Leonhout structure.

4.2.2 Onshore UK wells

Grove 3 (1981)

Grove-3 (Figure 4.7 and 4.8) was drilled on the southern flank of the Gainsborough Trough to evaluate a seismic anomaly which proved to be dolomitised Chadian limestones (Sequence S2). The dolomite is approximately 50m thick and occurs below a regional top Chadian sequence boundary. Examination of the one core cut suggests that the limestone was originally a bioclast grainstone or packstone with cross-bedded intervals and layers of coarse bioclastic lags resting on scoured surfaces. The depositional environment was a high energy setting above normal wave base with the development of bioclastic shoals with lower energy, sheltered areas between the carbonate shoals in which the wackestone beds were deposited.

The pore system is dominated by biomouldic pores (vugs) following the dissolution of crinoid ossicles, these are often lined by bitumen. Core porosities range between 1.4% and 12.5%, average 7.8%, with permeabilities of between 0.04 and 10.1mD, average 0.56mD. A DST of this interval flowed formation water at 220 bpd.

Nettleham (1982)/Nocton (1944)

Nettleham-1 was drilled on the south-east margin of the Gainsborough and encountered a 60m thick Asbian limestone which was brecciated, fractured and vuggy. The fractures and vugs contained live oil. Core analysis from a 10m interval gave a mean porosity of 5.3% and a mean permeability of 1.3mD, range 0.04 to 5.4mD. The core showed abundant hairline fractures in addition to a larger fracture system and intergranular pores. The limestone was fractured over a 29m thick interval which, when tested by a DST, indicated a permeability of 1.1Md, which is in good agreement with the core analysis data. Core analysis from the subsequent drilling of Nettleham-2, over a 52m thick interval, showed a range of porosity from 10.8% to 19.5% (average of 15.2%) and the mean permeability of the most porous interval was 3.3mD.

Milton Green - 1 (1965)

Milton Green-1 (Figure 4.9) penetrated a 50 feet thick dolomite interval (no age dating available) some 850 feet below the top of the Dinantian. This interval was partially cored and the dolomite was described as fossiliferous and porous with vugs up to ½ inch in diameter. A DST overt this interval flowed salt water (37,000 ppm NaCl) to surface at an estimated rate of 1915 bpd suggesting the development of reservoir quality carbonates.

Strelley - 1 (1986)

Strelley – 1 (Figure 4.10) was drilled on the northern margin of the Widmerpool Gulf to test a four-way dip closure at top Dinantian level. The well penetrated a 371.5m thick volcanic section at the top of the Dinantian and the four-way dip closure is likely to have been formed by drape over this volcanic mound. Below the volcanics, the well penetrated carbonates of probable Chadian age with severe mud losses of 160 bbls/hour. Two bit drops were reported between 1326.5 – 1327m and 1329.5 – 1330.5m, and these are interpreted as karstified surfaces possibly associated with the Chadian sequence boundary. A cased hole DST over this interval (1326 – 1336m) flowed an equivalent of 2000 bwpd before having to been abandoned due to high H_2S levels.

Somerton -1 (1969)

Somerton-1 (Figure 4.11) encountered 400 feet of Asbian – Brigantian dolomites with one 58 feet core taken at the top of the interval. Porosities are described as excellent in the packstone and grainstone intervals where it includes inter-crystalline and biomouldic pores. The cored interval also shows numerous hairline sub-vertical fractures. An episode of dissolution resulted in the enlargement of both fractures and matrix pores and the formation of vugs up to 3 inches in size. These vugs and open fractures were exploited by mineralization and the deposition of galena, sphalerite, pyrite and calcite.

4.3 Evidence of reservoir development – from outcrops.

As summarised on Figure 4.0 there is a wide variety of outcrop evidence from the UK and Belgium for the development of karstified and fractured intervals in the Dinantian. One of the best examples is from Castleton in Derbyshire where an Asbian carbonate shelf margin is exposed and is onlapped by Namurian (Edale) shales (Figure 4.12). Due to the top of this sequence being completely impregnated by bitumen and underlying vugs and fractures being lined or filled by bitumen it has been suggested that this shelf edge represents an exhumed oil field. The limestones are bioclastic grainstones and packstones deposited in a high-energy environment and exhibit the following features:

Cave, cavern and fissure systems
Dissolution features
Fracturing associated with mineralization
Breccias and boulder beds
Stacked karst surfaces.

There are clear similarities between the reservoir quality of the carbonates found at Castleton and at Heibaart, both locations exhibit highly karstified, fractured and mineralised carbonates. These two examples represent some of the best reservoir characteristics found in the Dinantian carbonates in the region. There is a possible twofold explanation for this:

1. The elevated, rimmed platform margins have been more exposed at time of sea-level falls and consequently more intensely karstified, and
2. The junctions between the platforms and basins are often controlled by deep, underlying faults which appear to be the conduit for mineralising fluids which can enhance both fractures and karstic features.

Outcrops, particularly from Belgium, indicate that karstified features at the top of the Dinantian can be infilled by Namurian shales which will significantly reduce reservoir quality (Figure 4.13). Evidence, from Heibaart and Castleton, suggests that later circulating fluids are important in leaching and enhancing the pre-existing fracture and karst networks.

4.4 Global examples of carbonate reservoirs

Carbonate rocks ranging in age from Cambrian to Late Cretaceous form globally important reservoirs providing encouragement for the development of reservoir quality carbonates in the Dinantian. A few global examples are listed below:

Kharyaga Field, Timan-Pechora, CIS. Devonian carbonates. Reserves 215mmbo. Karstic and fractured reservoir. Oil column 418m. Permeability 10mD to Darcies. Karstified fractures, caves and vugs.

Yanglin Field, China. Cambro-Ordovician carbonates. Oil column 140m. Reserves 60mmbo. Porosity 2-3%, permeability up to 5000mD. Fractures, karstified fractures and vugs.

Palm Valley Field, Amadeus basin, Australia. Ordovician carbonates, gas column 670m. Porosity 2-8%, permeability).01 – 0.03mD. Highly fractured.

Yates, USA. Permian carbonates. Reserves 2 billion barrels. Oil column 150m. Porosity 10-15%, average permeability 120mD. Caverns and vugs.

Nagylengyel, Hungary. Triassic and Cretaceous carbonates. Oil column 100m. Porosity 1-2%. Karstified, thermal karst and fractures.

4.5 Conclusions

The wells which have penetrated the Dinantian and which are available for this study, are old and poorly documented. In addition, in the absence of any significant hydrocarbon discovery at this level and consequent lack of DST data the connectivity of karst and fracture networks is highly uncertain.

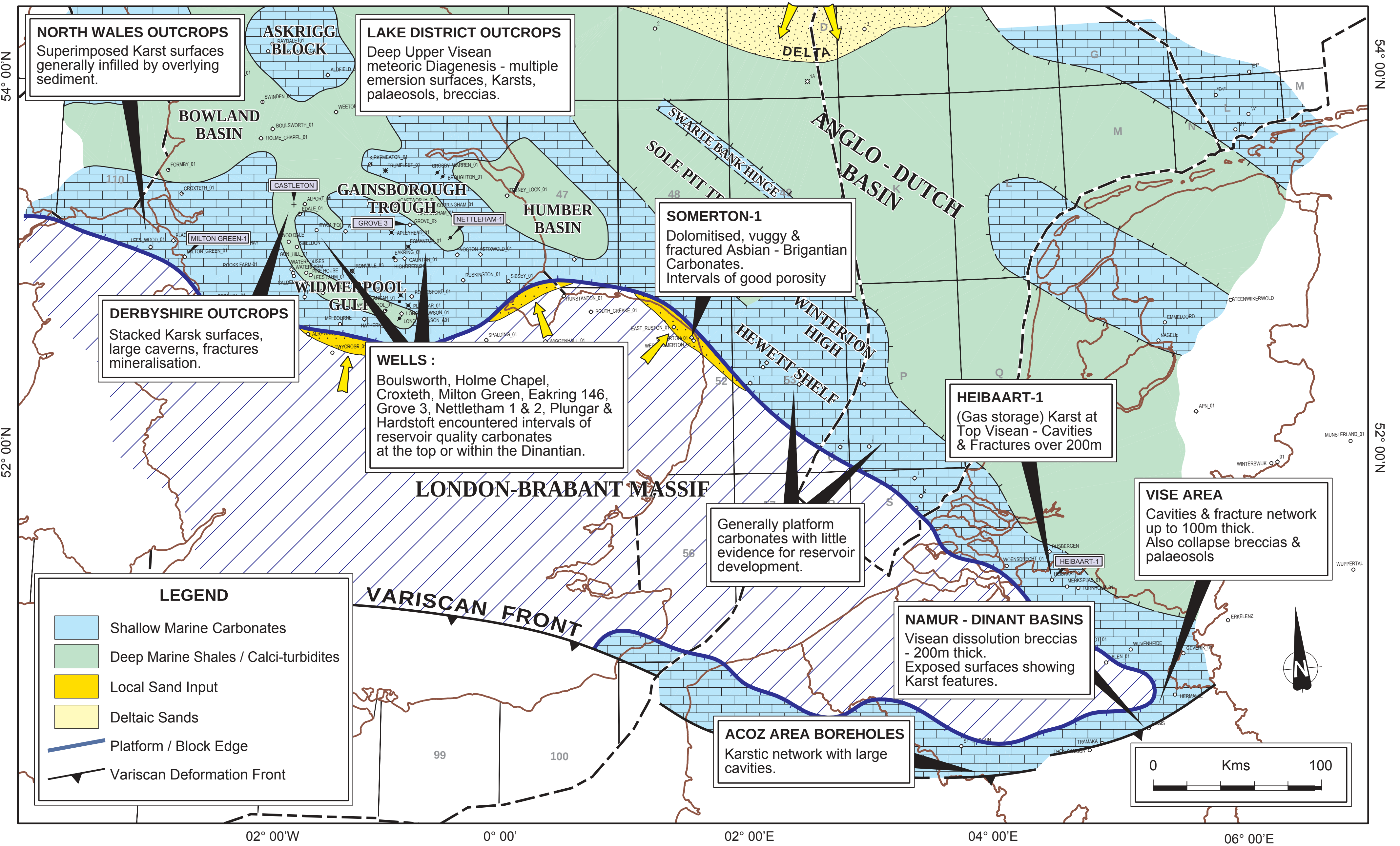
Analysis of the above information suggests the development of two principle reservoirs within the Dinantian, these are:

1. Intra-Dinantian carbonates, generally of Arundian-Chadian age and developed some distance below the top Dinantian. They are dolomitised and can show the development of karstic surfaces and fractures e.g. Grove-3, Milton Green -1 and Strelley. The overlying, non-dolomitised limestones are often tight.

2. Top Dinantian carbonates, generally of Asbian-Brigantian age can exhibit a karstic and fracture networks e.g. Castleton, Heibaart, Nettleham, Nocton, Hardstoft, Eakring and Plungar. Of these examples, Castleton and Heibaart, located at the platform margin and overlying possibly deep-seated faults show the best reservoir quality. The effects of sea-levels drops and consequently karstification is thought to have strongest at the platform margins, while mineralising fluids traveling up deep faults could have enhanced the karst and fracture network further.

Regional Review of the Dinantian Carbonate Play - Southern North Sea & Onshore U.K.

Dinantian Carbonate Reservoir Summary Map



NORTH WALES OUTCROPS
Superimposed Karst surfaces generally infilled by overlying sediment.

LAKE DISTRICT OUTCROPS
Deep Upper Visean meteoric Diagenesis - multiple emersion surfaces, Karsts, palaeosols, breccias.

DERBYSHIRE OUTCROPS
Stacked Karsk surfaces, large caverns, fractures mineralisation.

WELLS :
Boulsworth, Holme Chapel, Croxteth, Milton Green, Eakring 146, Grove 3, Nettletham 1 & 2, Plungar & Hardstoft encountered intervals of reservoir quality carbonates at the top or within the Dinantian.

SOMERTON-1
Dolomitised, vuggy & fractured Asbian - Brigantian Carbonates.
Intervals of good porosity

HEIBAART-1
(Gas storage) Karst at Top Visean - Cavities & Fractures over 200m

VISE AREA
Cavities & fracture network up to 100m thick.
Also collapse breccias & palaeosols

Generally platform carbonates with little evidence for reservoir development.

NAMUR - DINANT BASINS
Visean dissolution breccias - 200m thick.
Exposed surfaces showing Karst features.

ACOZ AREA BOREHOLES
Karstic network with large cavities.

LEGEND

🟦	Shallow Marine Carbonates
🟩	Deep Marine Shales / Calci-turbidites
🟨	Local Sand Input
🟨	Deltaic Sands
—	Platform / Block Edge
▼	Variscan Deformation Front

Figure 4.0

Porosity Distribution versus Karst Zonation

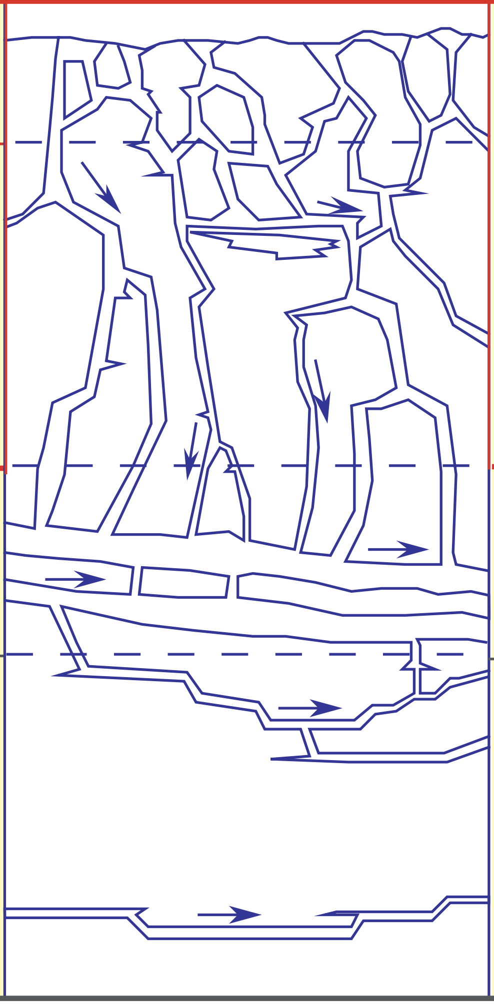
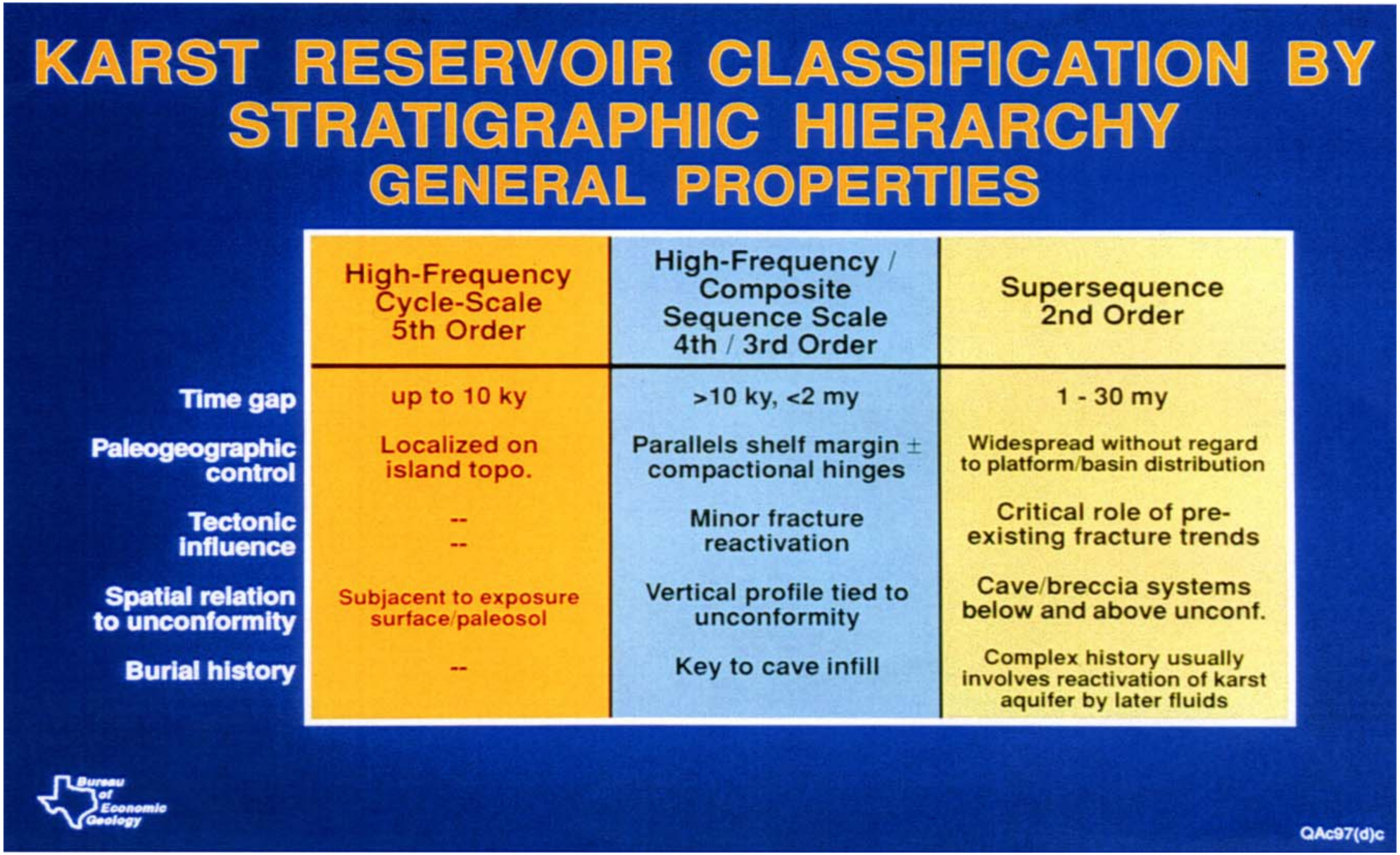
ZONATION	AVERAGE POROSITY	KARSTIC VOIDS ORGANIZATION	PALEO- DRAINAGE PATTERN	
Upper Vadose Zone(0 to 20 m)	1.15%		Vertical circulation (locally horizontal on shale screen)	
Lower Vadose Zone (50 to 75 m)	0.75%			
Upper Phreatic Zone(20 to 30 m)	2.75%		High speed	Horizontal circulation
Deep Phreatic Zone (> 200 m)	0.70%		Low speed	

Figure 4.1

Karst Development vs Time - RCRL

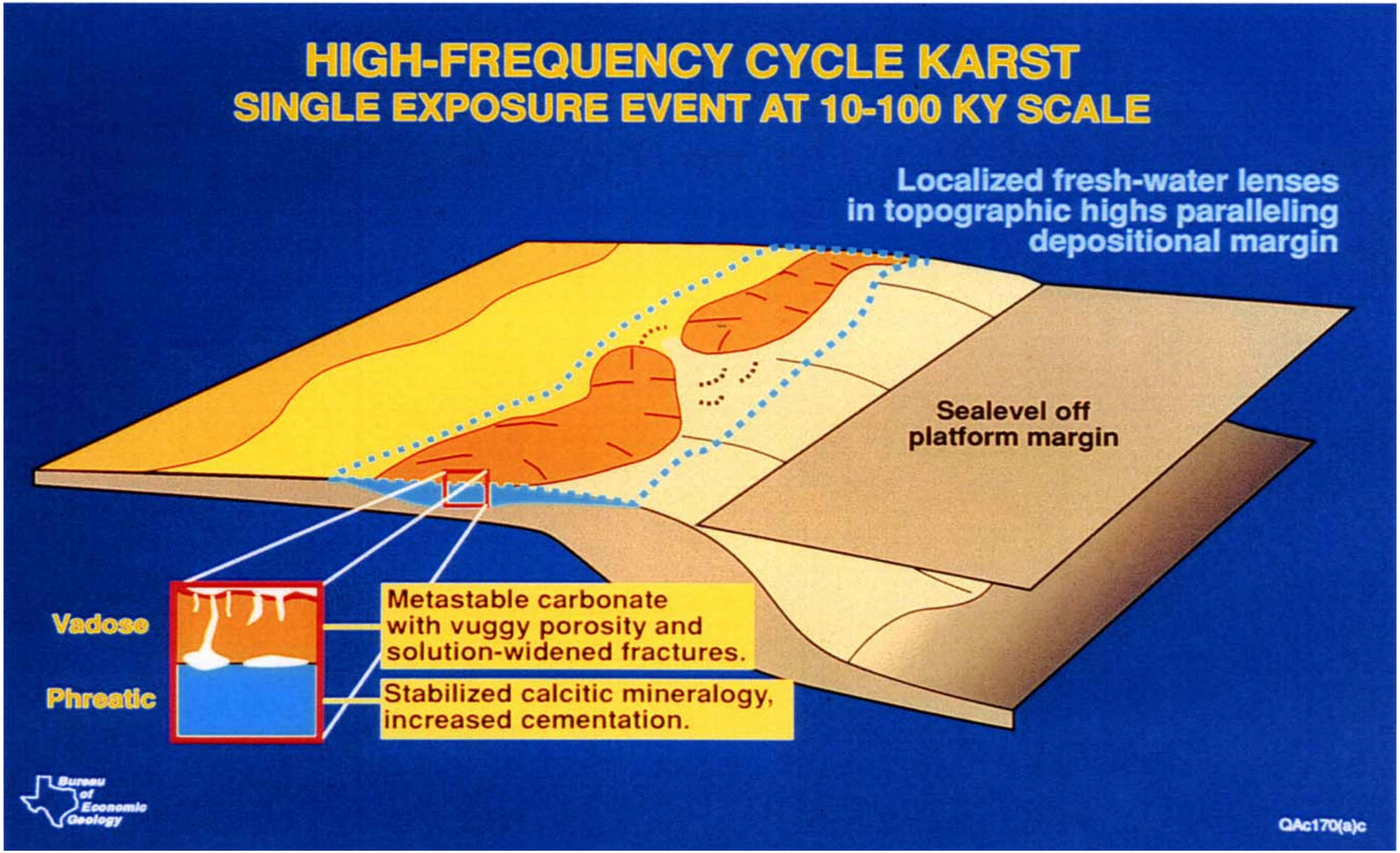


KARST RESERVOIR CLASSIFICATION BY STRATIGRAPHIC HIERARCHY
GENERAL PROPERTIES

	High-Frequency Cycle-Scale 5th Order	High-Frequency / Composite Sequence Scale 4th / 3rd Order	Supersequence 2nd Order
Time gap	up to 10 ky	>10 ky, <2 my	1 - 30 my
Paleogeographic control	Localized on island topo.	Parallels shelf margin ± compactional hinges	Widespread without regard to platform/basin distribution
Tectonic influence	-- --	Minor fracture reactivation	Critical role of pre-existing fracture trends
Spatial relation to unconformity	Subjacent to exposure surface/paleosol	Vertical profile tied to unconformity	Cave/breccia systems below and above unconf.
Burial history	--	Key to cave infill	Complex history usually involves reactivation of karst aquifer by later fluids

Figure 4.2

Karst Development 5th Order - RCRL



HIGH-FREQUENCY CYCLE KARST
SINGLE EXPOSURE EVENT AT 10-100 KY SCALE

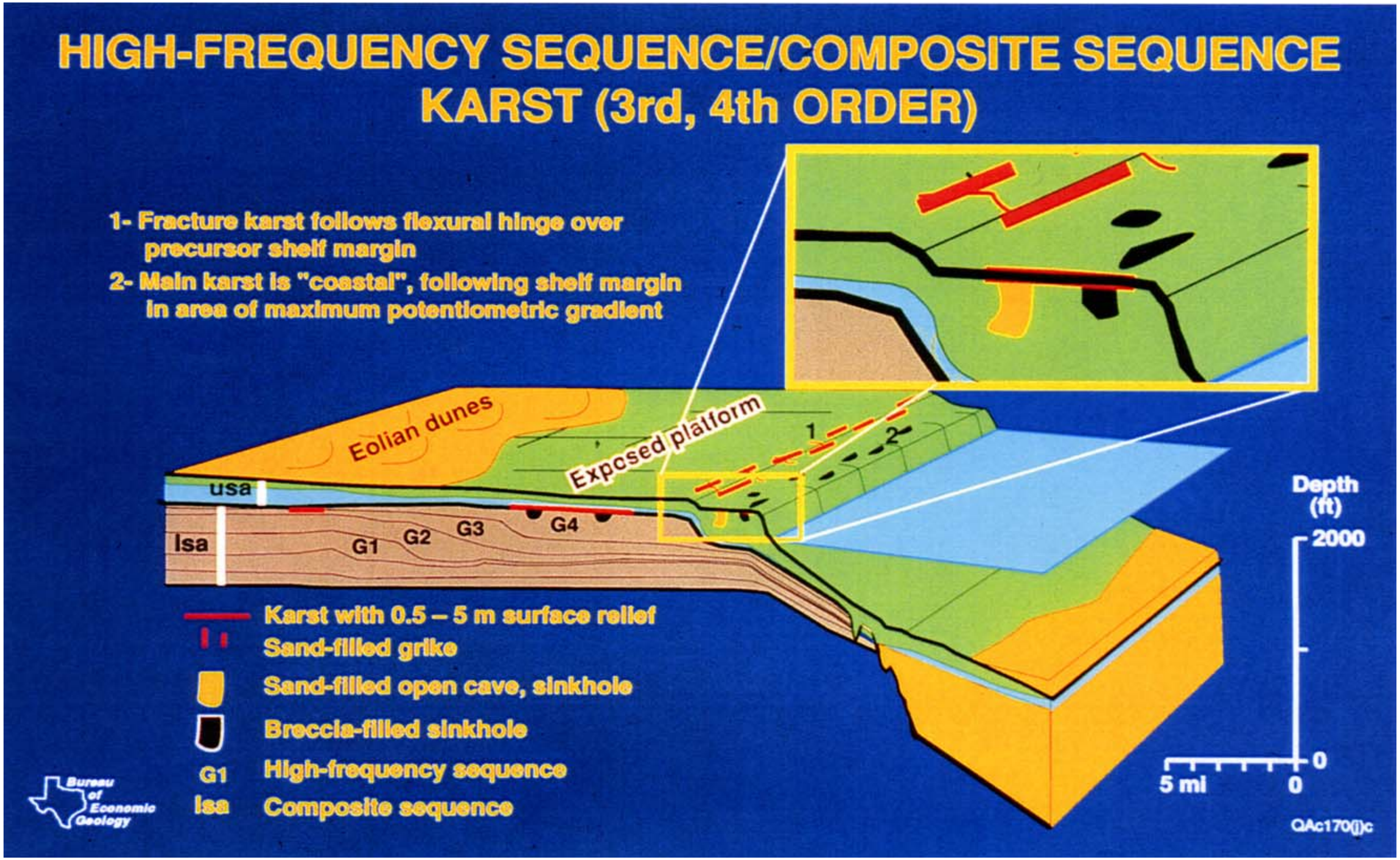
Localized fresh-water lenses in topographic highs paralleling depositional margin

Metastable carbonate with vuggy porosity and solution-widened fractures.

Stabilized calcitic mineralogy, increased cementation.

Figure 4.3

Karst Development at 3rd & 4th Order



HIGH-FREQUENCY SEQUENCE/COMPOSITE SEQUENCE KARST (3rd, 4th ORDER)

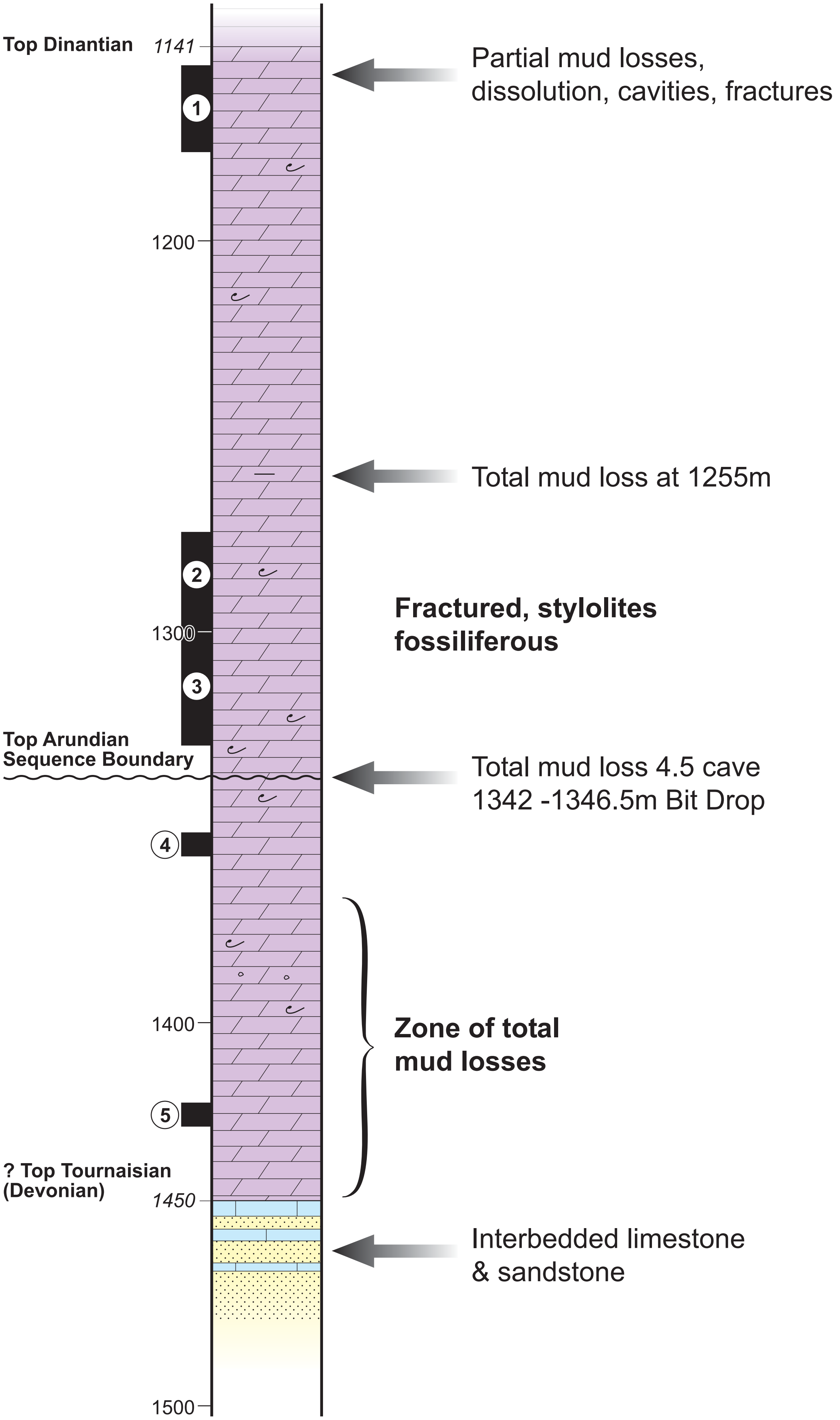
1- Fracture karst follows flexural hinge over precursor shelf margin

2- Main karst is "coastal", following shelf margin in area of maximum potentiometric gradient

Figure 4.4

Regional Review of the Dinantian Carbonate Play - Southern North Sea & Onshore U.K.

Dinantian Reservoir Section (Belgium) - Heibaart 1 Well



Partial mud losses, dissolution, cavities, fractures

Total mud loss at 1255m

Fractured, stylolites fossiliferous

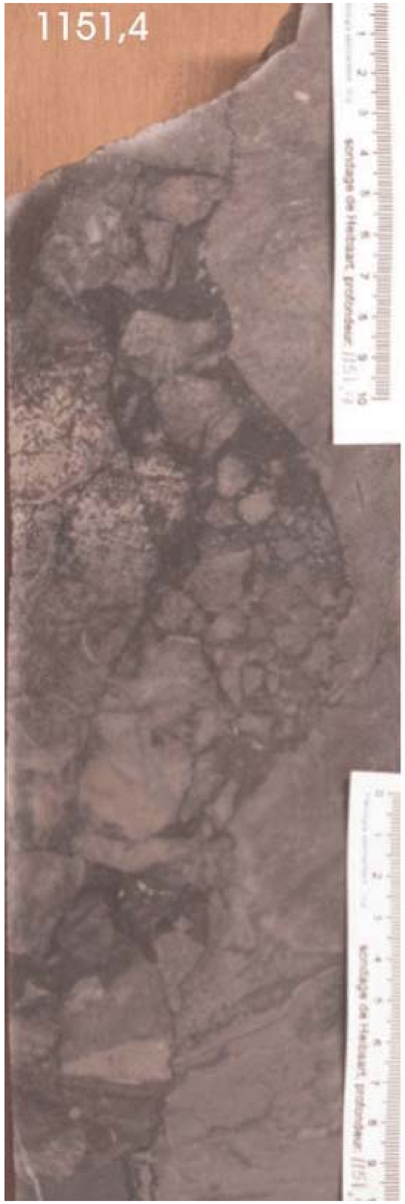
Total mud loss 4.5 cave 1342 -1346.5m Bit Drop

Zone of total mud losses

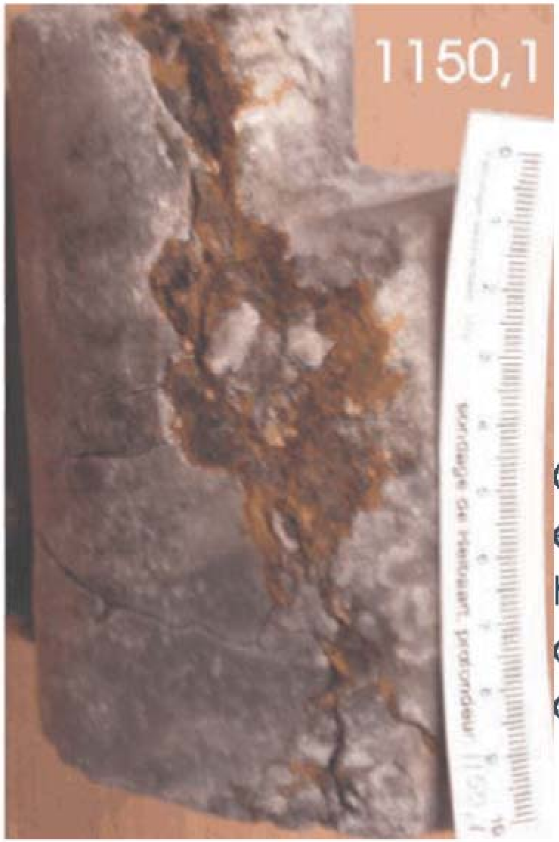
Interbedded limestone & sandstone

Figure 4.5

Dinantian Reservoir Section : Heibaart-1 Core Fractures



Enlarged fracture, enhanced by hydrothermal fluids circulations with breccia fill



Open fracture, enhanced by hydrothermal fluids circulations and covered by Sulphides

Origin TG/ISS/CARB - Winterton - Tentative geological model

Figure 4.6

Dinantian Reservoir Section - Grove 3 Well

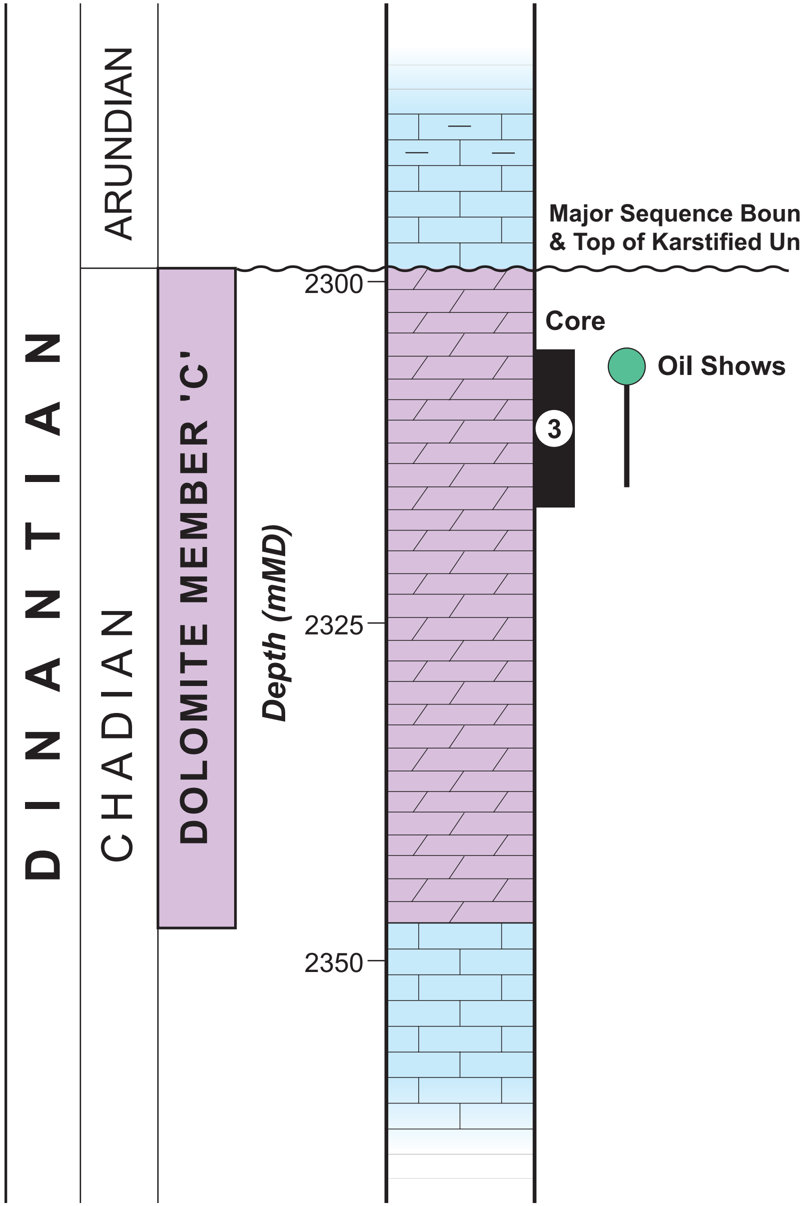


Figure 4.7

Dolomite Member 'C'

Dolomite Member 'C'

medium-coarse crystalline, sucrosic, shelly, vuggy, bitumen line vugs

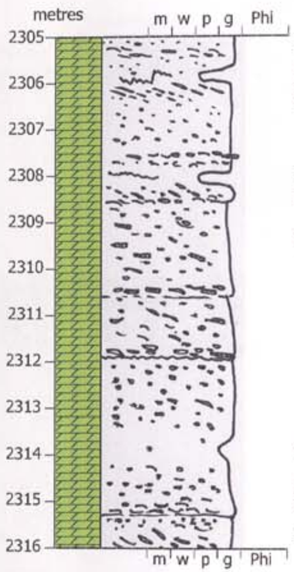
Reservoir

Gross : 50m
Porosity Range : 1.4 - 12.5%
Average Porosity : 7.8%
Permeability Range : 0.04 - 10.1mD
Average Permeability : 0.56mD

Regional Review of the Dinantian Play - Southern North Sea & Onshore UK

Grove-3 Core 3

ummary core 3: Originally deposited as high energy moderate to well sorted rainstone in carbonate sand-body at a carbonate shelf margin or shallow amp setting. Replaced by sucrosic dolomite.
Vell site description refers to vugs in the core as being lined by bitumen. The nterval tested at 220bbls water pd.



Core 3: Possible Chadian

Sub-horizontal alignment of biomoulds in dolograinstone.

Dolowackestone with denticular stylolite overlies dolograinstone with possible cross-bedding defined by oblique alignment of biomoulds.

Dolowackestone interval grades up into dolopack/grainstone

Possible scoured surface with bioclastic lag.

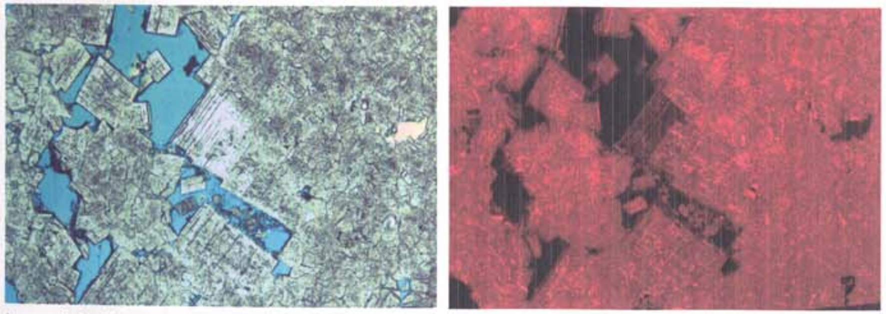
Moderately sorted crinoidal dolograinstone/packstone.

Wackestone interval with few crinoid biomoulds.

Abrupt change in biomould size and coarser layers with sub-horizontal alignment of biomoulds.

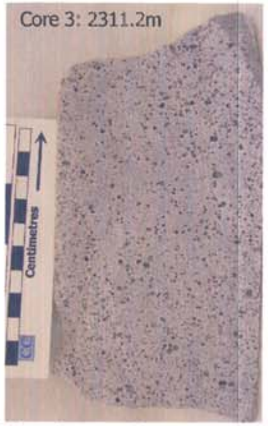
Oblique alignment of biomoulds that may represent cross-bedding.

The entire cored interval has been replaced by mesocrystalline, anhedral to subhedral dolomite that has poor intercrystal porosity but abundant biomoulds of disarticulated and abraded crinoid ossicles and brachiopod shell fragments. Biomoulds are occasionally partly infilled by clear euhedral dolospar. The variation of depositional texture is picked out by variations in abundance and grain-size of biomoulds.



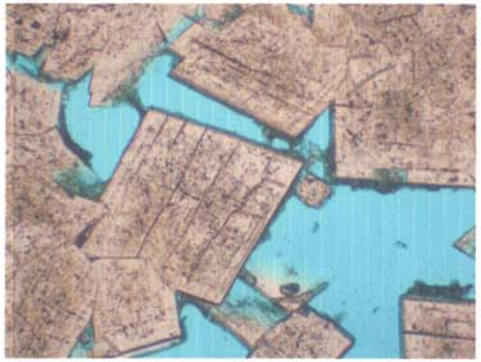
lane polarised light/CL pair showing inclusion-rich matrix dolomite with mottled CL texture suggesting recrystallisation of olomite with no indication of original texture. Biomouldic pores are lined by minor clear non-CL dolomite cement. 2309.95m eld of view 2.5mm

Dolowackestone with denticular stylolite and scattered biomoulds.



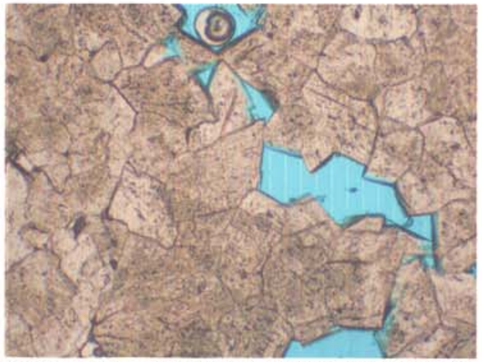
Dolograinstone with common biomoulds.

Dolograinstone with common biomoulds including dissolved crinoid ossicles.



Biomould in dolomite lined by eudedral dolomite cement. 2309.95m, field of view 5mm

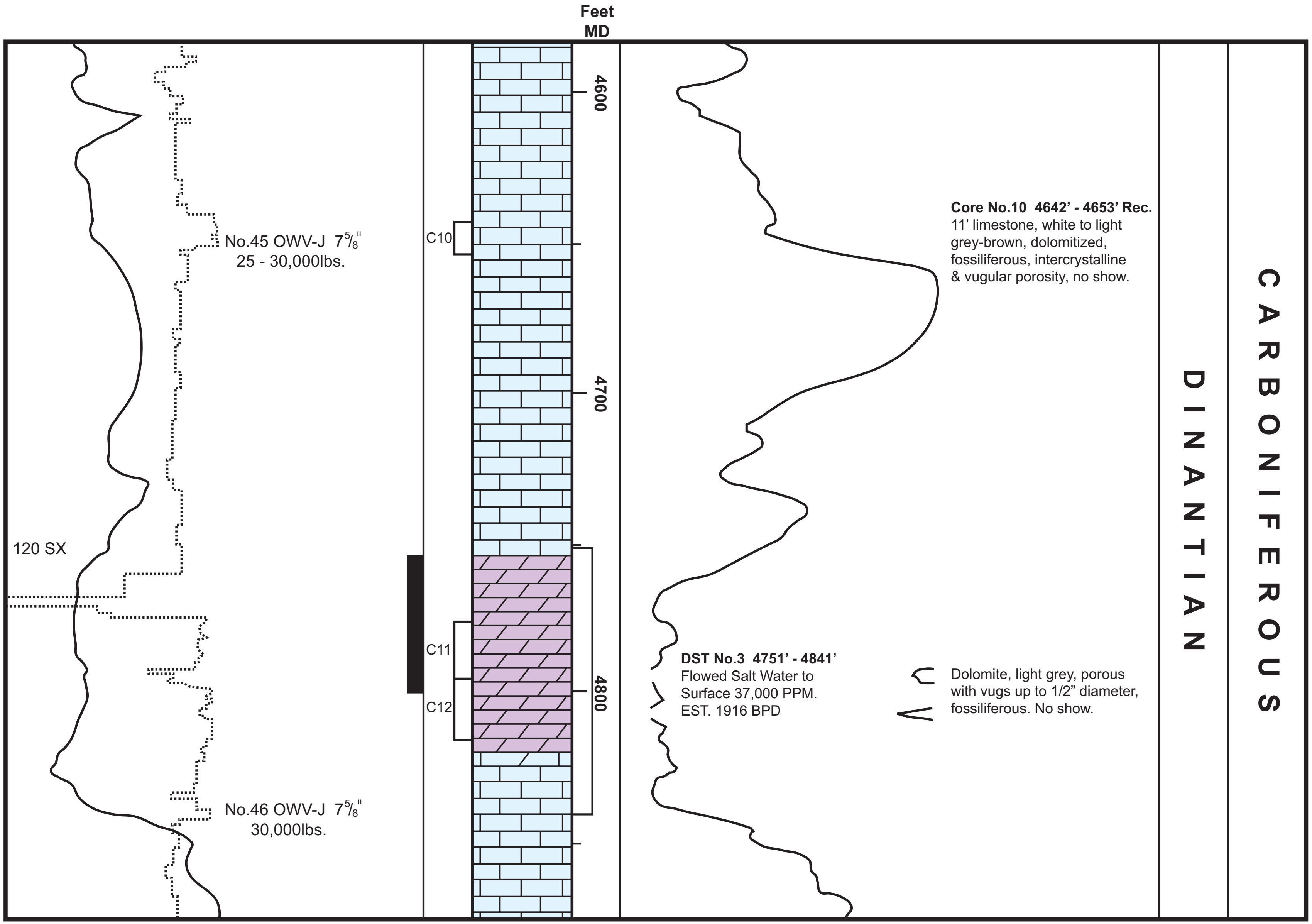
Dolograinstone with common dissolved crinoid ossicles and shell, possible cross-bedding defined by oblique alignment of biomoulds.



Dolomite with biomould lined by subhedral dolospar cement with poor intercrystal porosity in the matrix. 2311.35m, field of view 5mm

Figure 4.8

Milton Green - 1 (1965) Part of Dinantian Section



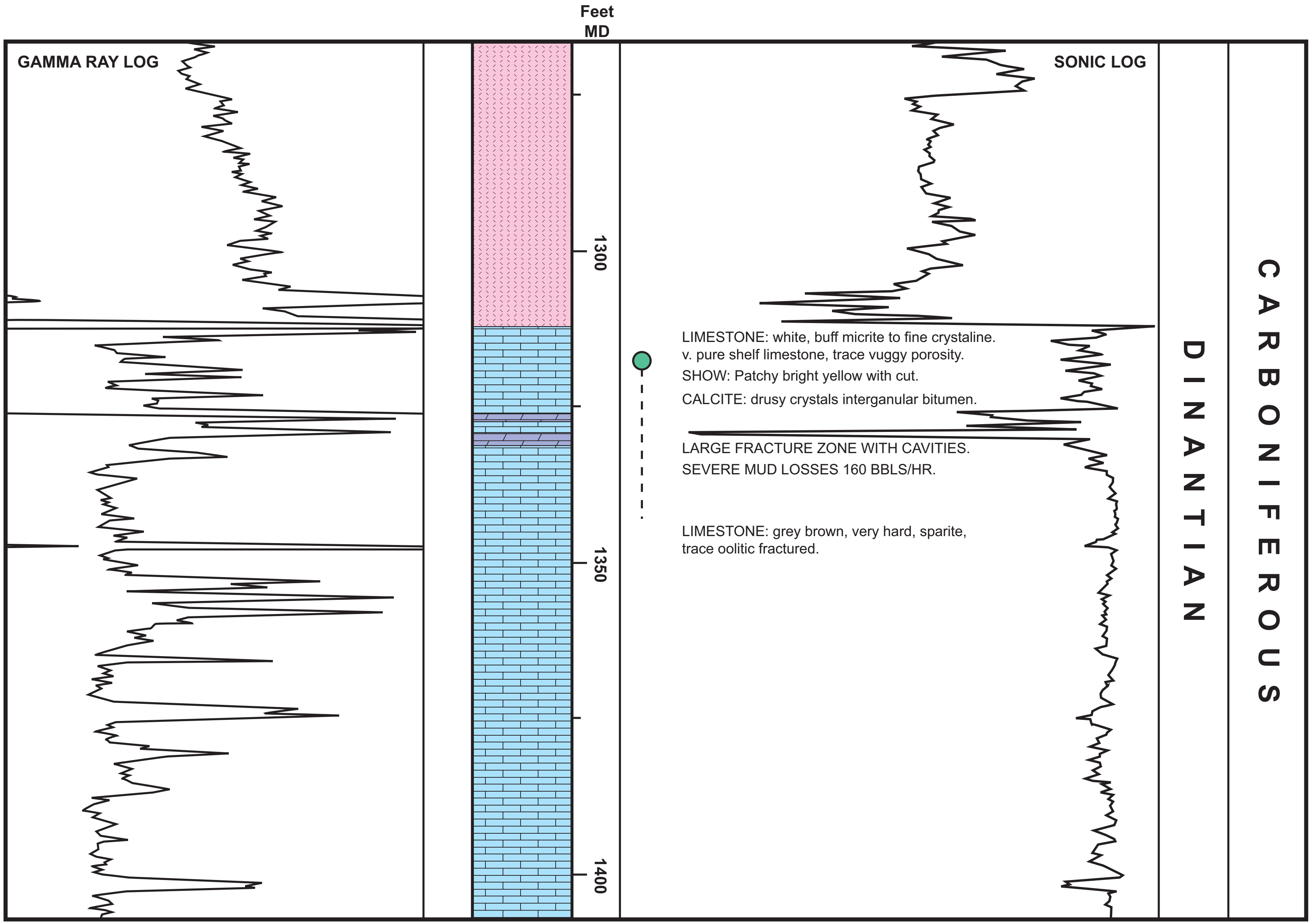
Core No.10 4642' - 4653' Rec.
11' limestone, white to light grey-brown, dolomitized, fossiliferous, intercrystalline & vugular porosity, no show.

DST No.3 4751' - 4841'
Flowed Salt Water to Surface 37,000 PPM. EST. 1916 BPD

Dolomite, light grey, porous with vugs up to 1/2" diameter, fossiliferous. No show.

Figure 4.9

Strelley-1



LIMESTONE: white, buff micrite to fine crystaline.
v. pure shelf limestone, trace vuggy porosity.
SHOW: Patchy bright yellow with cut.
CALCITE: drusy crystals interganular bitumen.

LARGE FRACTURE ZONE WITH CAVITIES.
SEVERE MUD LOSSES 160 BBLS/HR.

LIMESTONE: grey brown, very hard, sparite,
trace oolitic fractured.

Figure 4.10

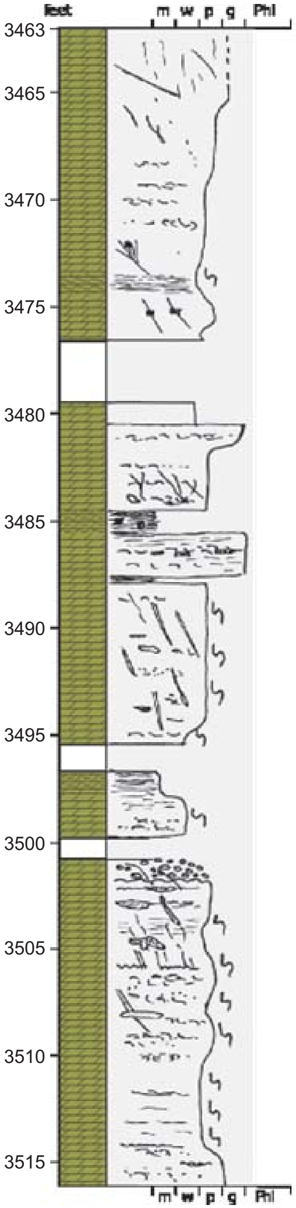
Somerton - 1 Asbian / Brigantian

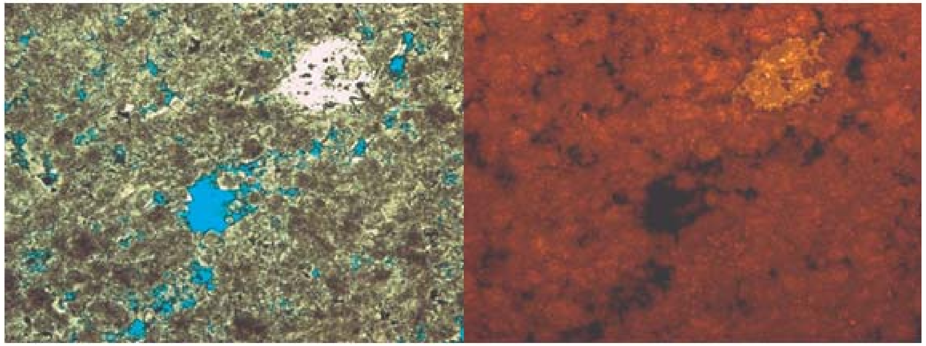
Replaces shelf carbonates

Moderate matrix porosity

?Karst enlarged fractures and vugs lined by sulphides

Burial then late low T minerals

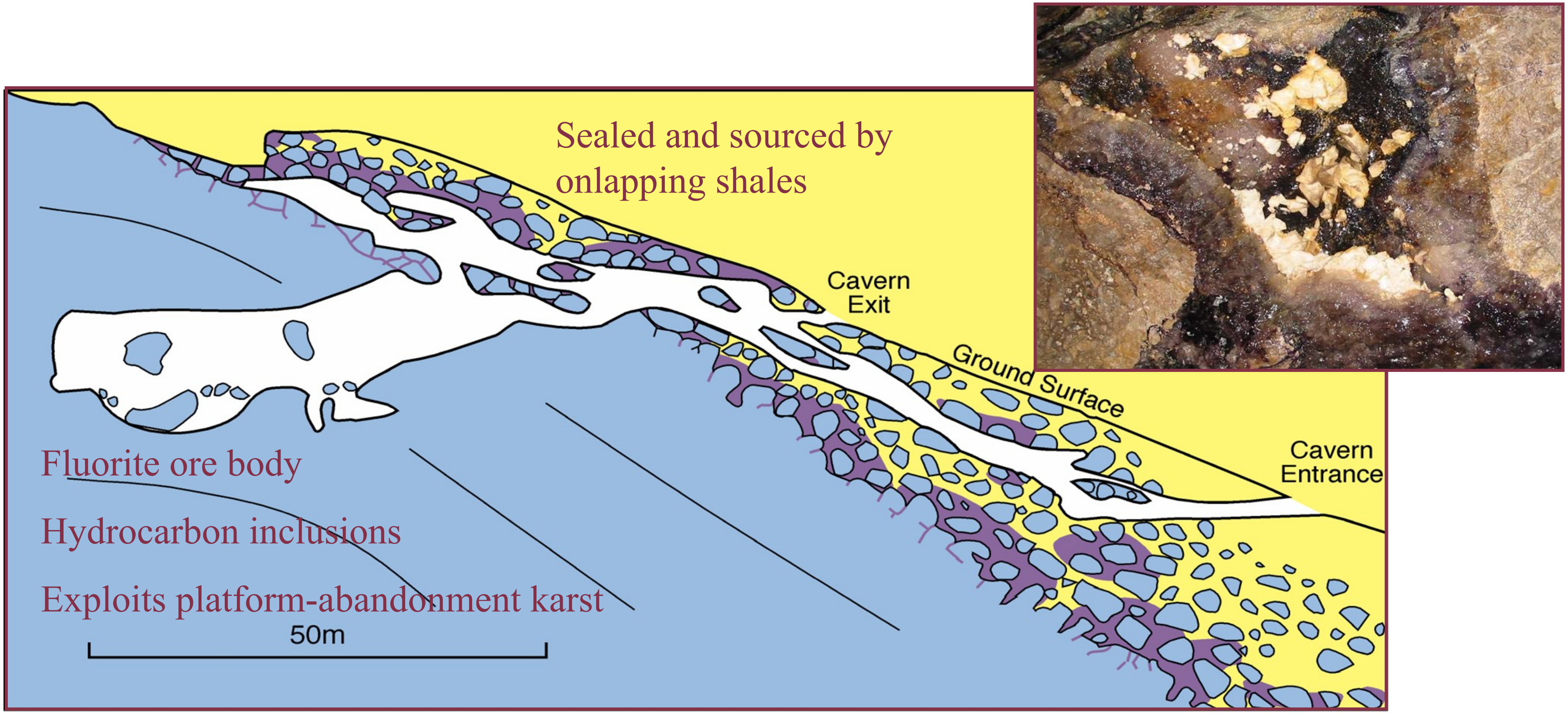




Origin P. Gutteridge, presentation Den Haag, Feb 2006

Figure 4.11

Shelf Margin Mineralisation



Sealed and sourced by onlapping shales

Fluorite ore body

Hydrocarbon inclusions

Exploits platform-abandonment karst

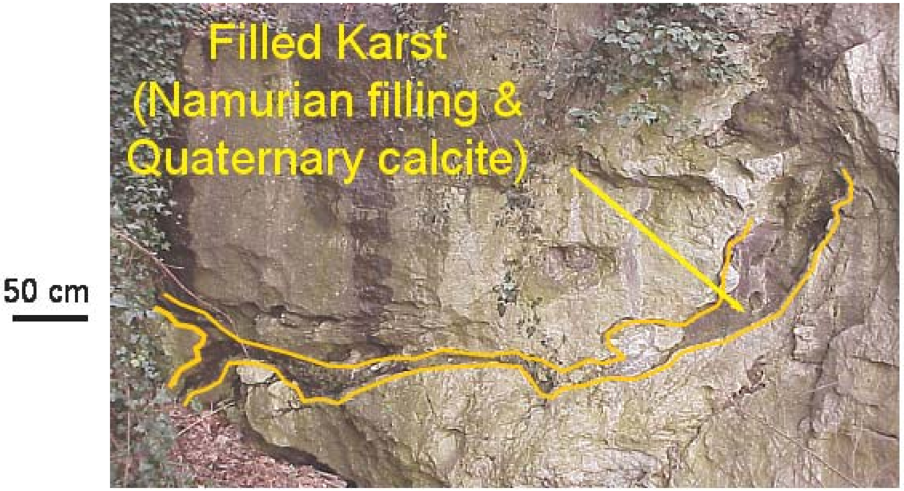
🟨	Edale Shales	▨	Limestone boulders
🟦	*In situ* shelf margin limestones	🟪	Mineralisation

Figure 4.12

Origin P. Gutteridge & N. Pickard, Cambridge Carbonates Ltd, March 2005

Regional Review of the Dinantian Carbonate Play - Southern North Sea & Onshore UK

Dinantian Reservior Section : Belgium, Viseán Karst - Argenteau Area



Late Visean to Dinantian karstification evidenced by Namurian cave fills

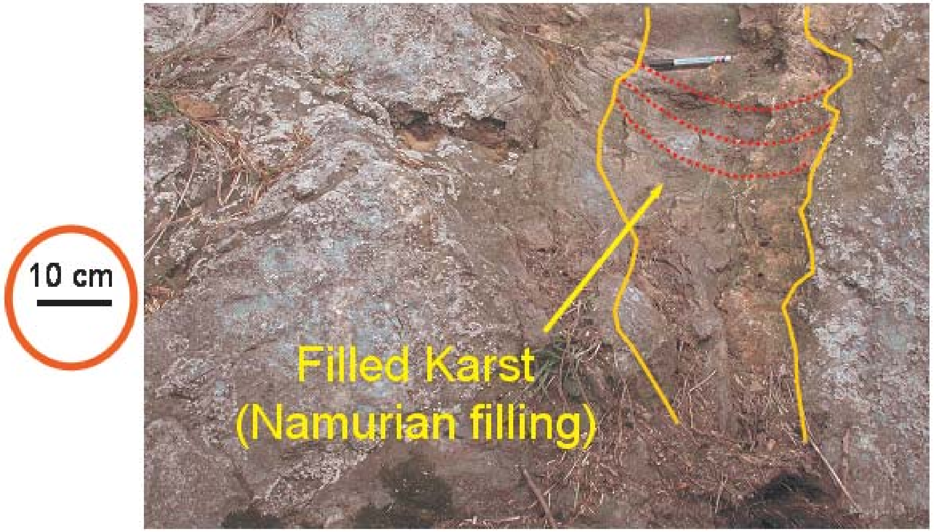


Figure 4.13

Origin TG/ISS/CARB - Winterton - Tentative geological model

5 SOURCE ROCKS & HYDROCARBON CHARGE

5.1 Introduction

Throughout much of the Southern North Sea area the source of the gas found in Upper Carboniferous, Rotliegend and Triassic reservoirs was generated from the thick coal-bearing Westphalian A and B sections. Due to the absence of migration routes between the above mentioned source rocks and the deeper Dinantian carbonate reservoirs, the source rocks invoked for the Dinantian Play are anoxic, deepwater, pro-delta shales developed in the early Namurian and possibly Dinantian. They generally form Type 2 source rocks. Communication between these source rocks and the carbonate reservoirs is possible either by direct onlap or fault juxtaposition.

As discussed in section 3.2 and illustrated on Figure 3.4 the basinal shales which form these source rocks are restricted to basins immediately to the north of the London-Brabant. Well and outcrop data indicate that these source rocks are developed in an east-west band of basins extending from Belgium and the Netherlands through the UK into Ireland. Offshore evidence for the presence of these source rocks comes from UK43/17-1, UK 48/3-3 and NP16-1. By comparison with onshore UK basins it considered likely that these source rocks are thickly developed in the Sole Pit Trough, Broad Fourteens and west Netherlands Basins. Fine-grained hemi-pelagic sediment was deposited in the deeper parts (200-300m water depth) of the relatively sediment starved half-grabens, while coeval ramp/platform carbonates formed in the shallow waters around basin margins. The fine-grained argillaceous sediment constitutes distal silliciclastics from a northern delta complex, eroding the old Caledonian hinterland. The deltas were confined to the north of the region in the Dinantian and Early Namurian but prograde progressively to the southeast during the late Namurian and Westphalian (Figure 3.5). The advance of this major deltaic system was diachronous as recorded by the occurrence of more proximal clastics in the northerly Northumberland Trough and Solway Basin in comparison to the deposition of similar successions in more southerly half-grabens. For this reason, the source rocks are best developed in the south of the study area such as in the Bowland Basin and Gainsborough Trough where distal fine-grained sediments were able to accumulate over a greater time interval.

Potential source rock intervals have been identified from outcrop in both the Dinantian and Namurian intervals. These potential source rock may be separated into three broad divisions, namely; intra-Dinantian, basal Namurian and intra-Namurian. The regional extent of these source rock intervals is displayed in Figure 3.4.

5.2 Intra-Dinantian Source Rocks

Potential intra-Dinantian source rocks correspond to transgressive events associated with the drowning of exposed carbonate platforms, as well as distal pro-delta sedimentation in the restricted half-grabens. The intra-Dinantian source rocks are present in areas such as the Gainsborough Trough, Edale and Widmerpool basins, but are absent in more northerly sub-basins such as the Northumberland Trough, Solway and Stainmore basins in proximity to the northern deltas. Intra-Dinantian source rocks are also known from the southern margin of the East Irish Sea Basin in northeastern Wales. Asbian-Brigantian oil shales (19% TOC) are also recorded in the Midland Valley of Scotland, but this facies development is considered to be laterally restricted and not representative of the intra-Dinatian source rocks as a whole.

5.3 Basal Namurian Source Rocks

The base of the Namurian succession is represented over much of the southern North Sea by shales which appear on gamma ray logs with a characteristic ‘hot shale’ spike. The basal Namurian shales form an excellent oil prone source rock with a residual TOC of 2-6%, and are able to generate either oil or condensate-rich gas. Deposition of basal Namurian source rocks was probably restricted to the southern and central parts of the Anglo-Dutch Basin by the early Namurian times due to the southerly prograding fluvio-deltaic facies to the north. In the U.K. the basal Namurian shales go by a number of different regional names such as the Bowland Shales, Sabden Shales, Edale shales etc. Fraser *et al*. (1990) recognised three intervals within the basal Namurian succession from outcrop studies in Derbyshire. They are summarised in Table 4.1

Interval Age		**Stratigraphic Thickness**	**Kerogen Type**	**Total Carbon Content (TOC)**	**Hydrocarbon Yield (kg/tonne)**
BASAL NAMURIAN	Late Arnsbergian - Marsdenian	5-15m intervals	Type II	Unknown	5-7
	Arnsbergian	~100m	Type II	Unknown	10-15
	Pendleian - Arnsbergian	80-200m	Type II	3-4%	10-15

Table 4.1 Potential source rock intervals and properties identified in the basal Namurian section in the Gainsborough Trough (Derbyshire).

Oil-source rock correlatations from the East Midlands prove the basal Namurian pro-delta shales as being the main source interval for the oil province. Recent discoveries in the East Irish Sea Basin have also been attributed to an early Namurian source - the Holywell shale formation. These shales are of Pendleian to Yeadonian age with TOC's ranging up to 5% and correlate well with oil in the Lennox and Douglas fields. The Namurian is also capable of generating substantial volumes of gas, as is demonstrated by the Morcambe gas fields in the East Irish Sea.

Residual oil shows (bitumen) in the carbonate platforms of Derbyshire are also thought to be derived from the adjacent Edale shales. A well known example of a breached oil accumulation is the Windyknoll elaterite, and seepages have long been observed in Derbyshire coal mines. Oil staining in the Rotliegend reservoirs of the Jupiter Fields (Quadrant 49) have also been attributed to oil-generation from a Namurian aged source.

In the Netherlands the basal Namurian shales are referred to as the Geverik Member. A sample analysed from the Geverik-1 well recorded a type II marine kerogen with a residual TOC of between 3-8%. This is despite the source rock being over-mature, Ro>4.5. It has a residual petroleum potential of 0.5kg hydrocarbon per tonne of rock. It is thought the Geverik member is widespread and prolific across the area.

Organic geochemical analyses of the basal Namurian shales from onshore Dutch wells; WSK-1 and GVK-1 confirm the Geverik Member as a good oil-prone source rock. Biostratigraphic correlation shows that the basal Namurian represents a major marine transgression with onlap onto the Dinantian palaeotopography.

5.4 Source Rock Maturity

In the southern North Sea, the marginal shelf areas are currently immature or have entered the early mature oil window (VR_o=0.5%-0.7%). In the deeper areas of the Southern North Sea basin near the platform margins, the maturity of the Carboniferous source rocks is greater than VR_o=1.00% (mid-mature oil window). The average source rock maturity along the flank of the London-Brabant massif is VR_o=1.5%. In the axial parts of sub-basins such as the inverted Sole Pit Trough, the maturity gradients are much greater and source rocks are currently mature for gas generation ($VR_o \geq$ 3.00%) (Figure 5.0).

5.5 Migration Pathways

Due to the interpreted onlapping geometry and transgressive nature of the early Namurian above the Dinantian carbonates, it is thought that where good quality carbonate reservoir exists, direct lateral charging of the reservoir could occur. Oil or gas generated in deep sub-basins could either directly charge the reservoir as a consequence of the onlapping geometry. Hydrocarbons could migrate laterally up dip to charge the reservoir and migration pathways would therefore be relatively short. This simple migration model is dependant on a robust Namurian cover with high shale content to prevent simple vertical migration into younger strata. The average horizontal migration distances from the source-kitchen in the East Midlands is 5km with a maximum of 12km, so proximity to a deep Dinantian depo-centre is a play requirement.

5.6 Timing of Hydrocarbon Generation

A distinct phase of pre-Variscan and post-Variscan hydrocarbon generation have been recognised from burial history modelling using well maturity data and fission track analyses.

5.6.1 Pre-Variscan

Maturation of the deeper parts of the Carboniferous succession in deep Dinantian depo-centres began prior to Variscan basin inversion. Hydrocarbons generated and trapped during this time are likely to have spilled during subsequent Variscan deformation, uplift and erosion.

The Bowland Basin, Cleveland Basin and parts of the Sole Pit Trough probably all reached maximum burial during the Carboniferous, with the only remnants of this early phase being bitumen occurrences in outcrop.

5.6.2 Post-Variscan

The Variscan Orogeny not only formed inversion structural trapping styles but ‘froze’ the hydrocarbon generation from Carboniferous source rocks which had been buried to a sufficient depth for an initial phase of oil generation to have occurred. The potential for success of the Dinantian carbonate play is largely dependant on the dominant period of hydrocarbon generation having taken place during the Mesozoic/Tertiary. Hydrocarbons generated during this later phase are capable of charging Variscan induced traps.

Fisson track studies in the East Midlands have confirmed that the dominant oil generation phase occurred over most of this area by the late Cretaceous. Mesozoic burial here was moderate and oil is the dominant hydrocarbon phase. Gas generation in the deeper basins such as the Gainsborough Trough and Widmerpool Gulf are modeled as having been relatively short-lived. Oil generation in the East Midlands ceased due to 1km of uplift during the Tertiary. Remigration may have also occurred as a result of late Tertiary eastward tilting.

No regional study has been undertaken on the relative timing hydrocarbon generation and migration in the offshore environment. In reality, it is likely to be highly variable depending on the thickness of the pre-Variscan and post-Variscan sedimentary thicknesses and the tectonic complexity. This critical parameter needs to examined a local, prospect scale.

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Schematic Distribution of Dinantian / E. Namurian Source Rocks

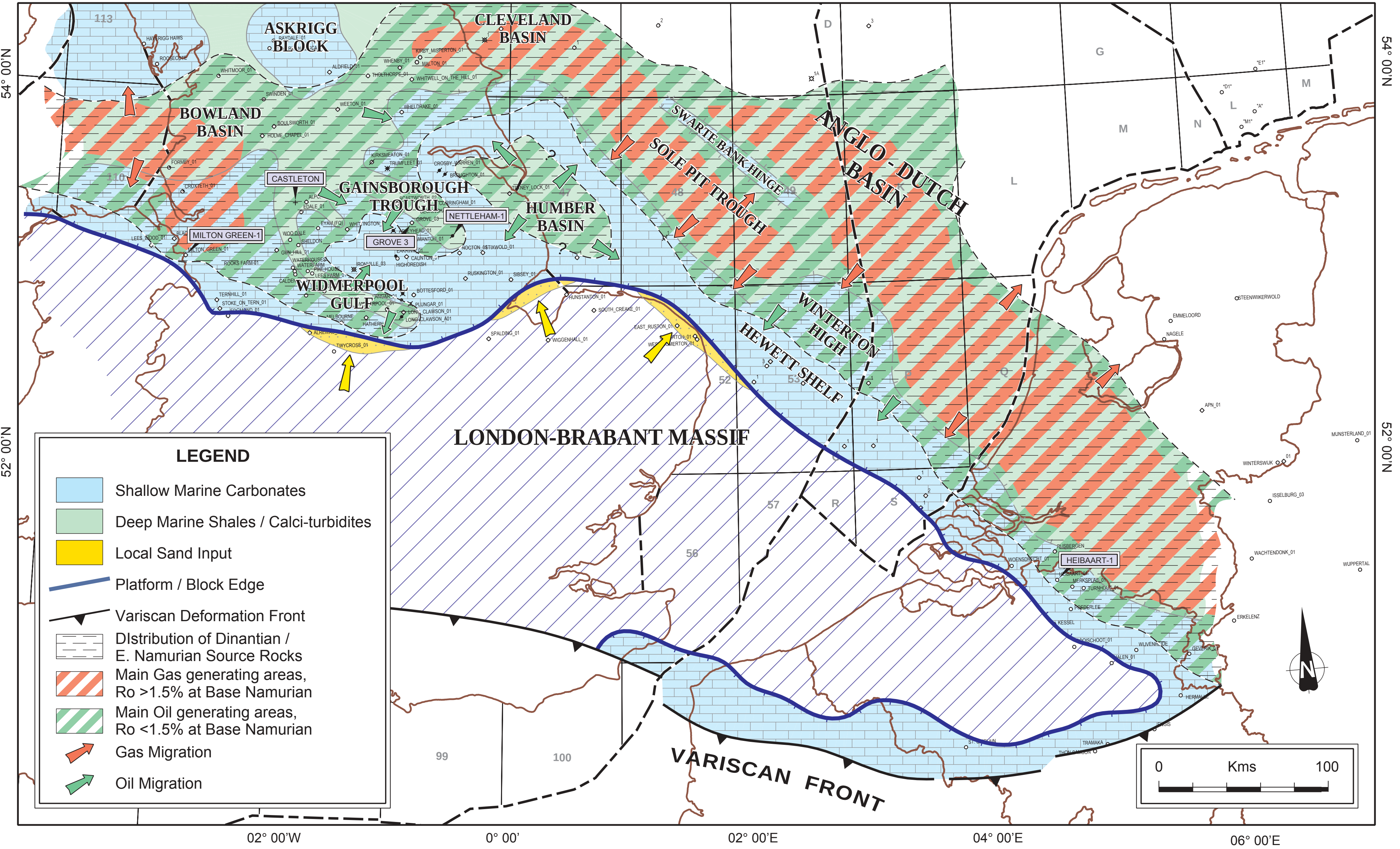


Figure 5.0

6 CONCLUSIONS

The Dinantian Carbonate Play represents an under-explored hydrocarbon play concept which warrants further exploration. Analysis of available data suggests that the play is most favourably developed at the carbonate platform margins with the adjacent basin. The reasons for this being:

> the position of the carbonate margins are often controlled by deep-seated faults which could have acted as the conduits for hydrothermal fluids which in turn can lead to the enhancement of the karstified reservoir.
>
> at the platform margins, the carbonates are possibly onlapped and overlain by Early Namurian source rocks resulting in possible direct hydrocarbon charge.

Critical risk factors to be evaluated on a local prospect scale include:

> source rock distribution
> the timing of hydrocarbon charge
> topseal effectiveness i.e. the thickness and lithological nature of the overlying Namurian, particularly sand/silt content.

An example of a Dinantian carbonate lead is found on the Winterton High and straddles blocks 53/5, 53/10, 54/1a and 54/6. This is referred to as the Winterton Lead and has been mapped on a deep, strong seismic reflector which has been regionally tied to the Top Dinantian carbonates (Figures 6.1 and 6.2). The lead comprises a large, north-south trending, faulted four-way dip closure with the crest at 4,300m subsea.

U.K.C.S. - Southern North Sea - Blocks 53/5c & 54/6 : Relinquishment Report (DTI)

Seismic Line 1500

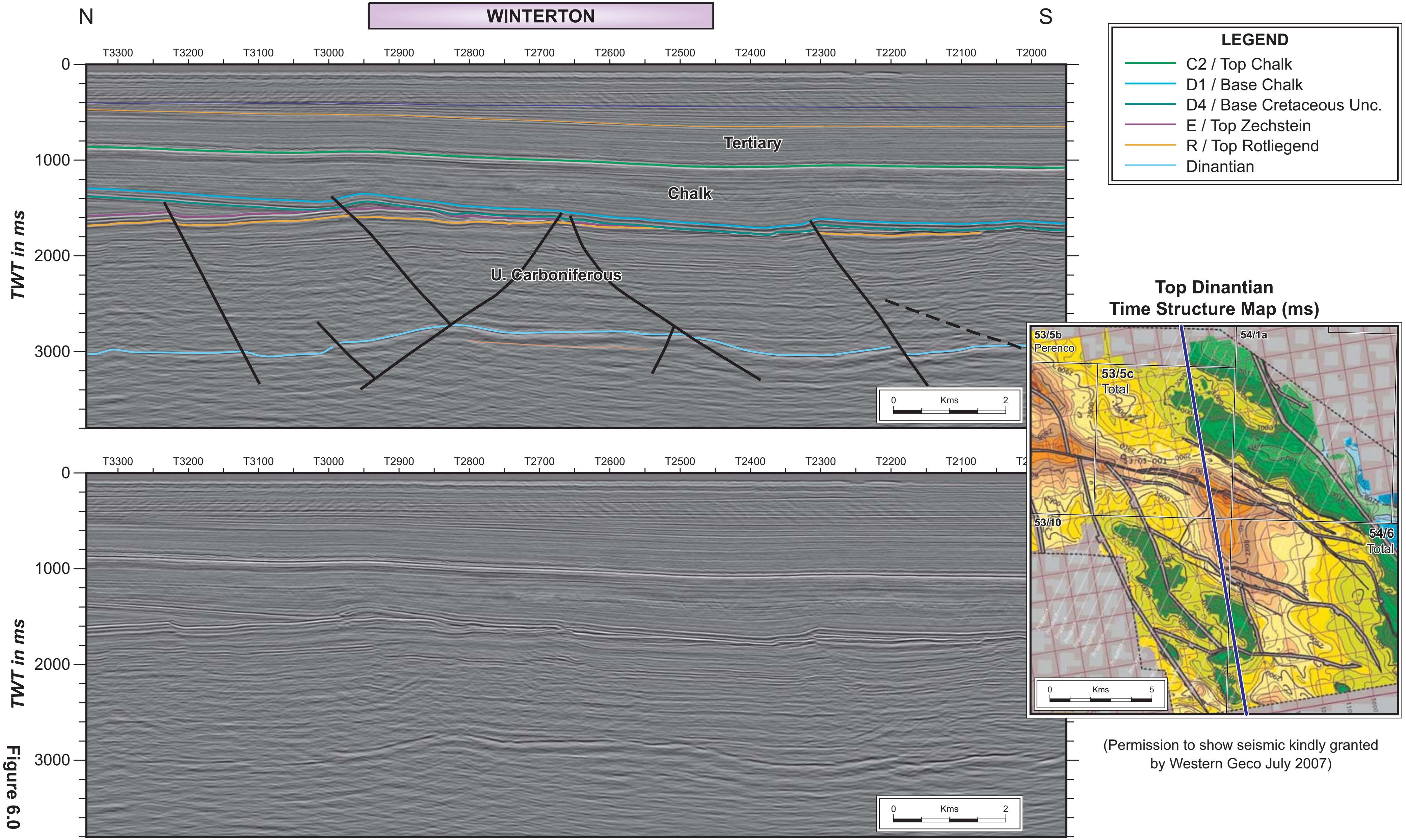
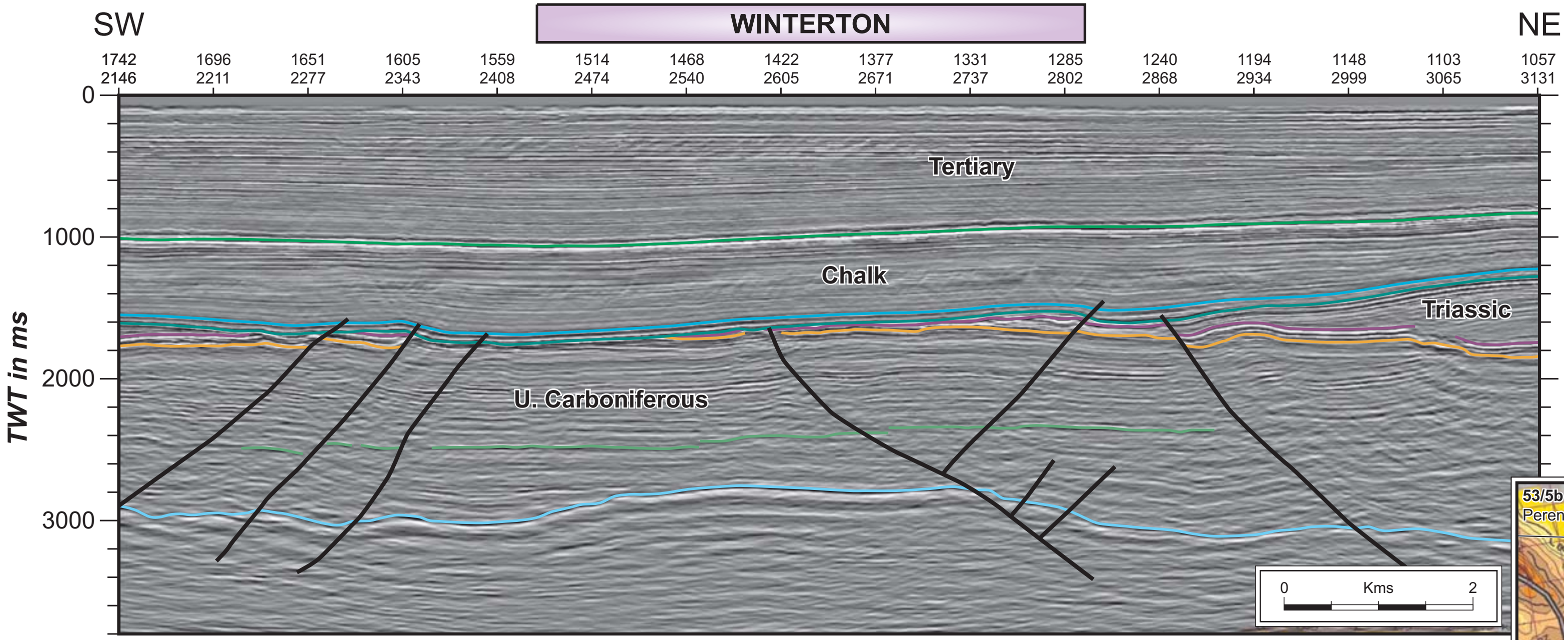


Figure 6.0

(Permission to show seismic kindly granted by Western Geco July 2007)

U.K.C.S. - Southern North Sea - Blocks 53/5c & 54/6 : Relinquishment Report (DTI)

Random Seismic Line 1000



LEGEND

- C2 / Top Chalk
- D1 / Base Chalk
- D4 / Base Cretaceous Unc.
- E / Top Zechstein
- R / Top Rotliegend
- Intra Namurian
- Dinantian

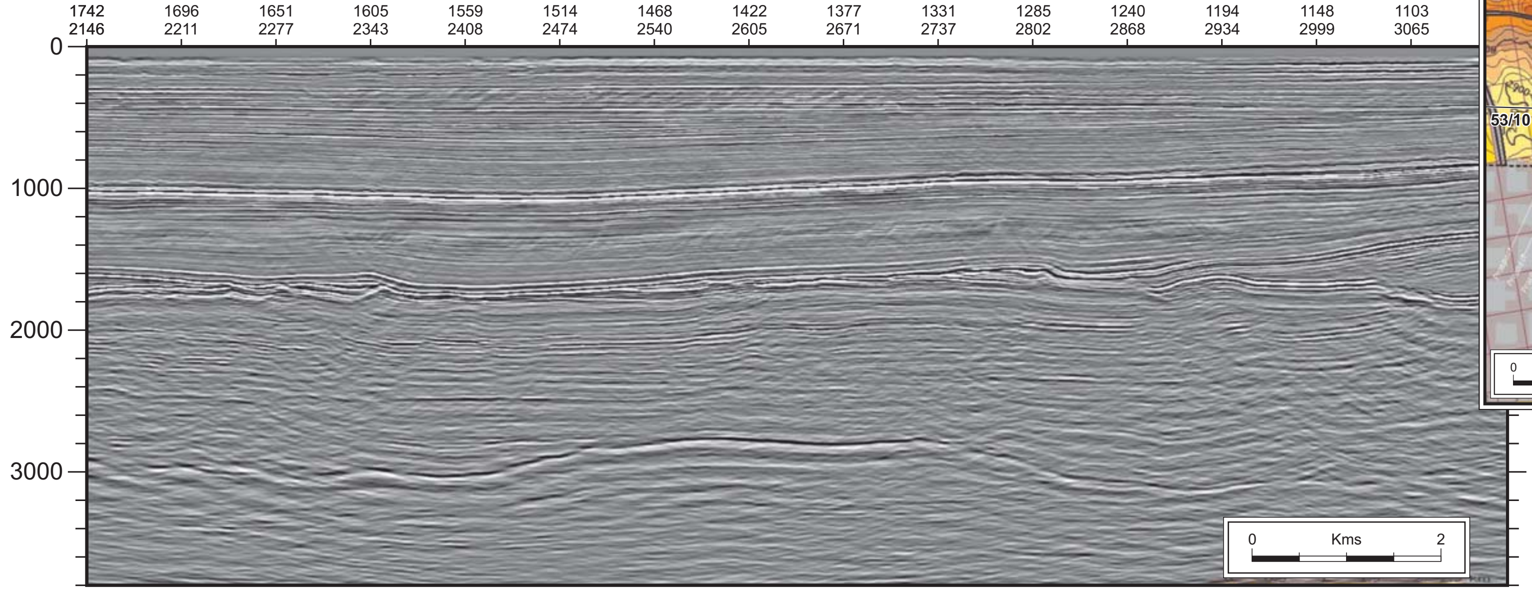
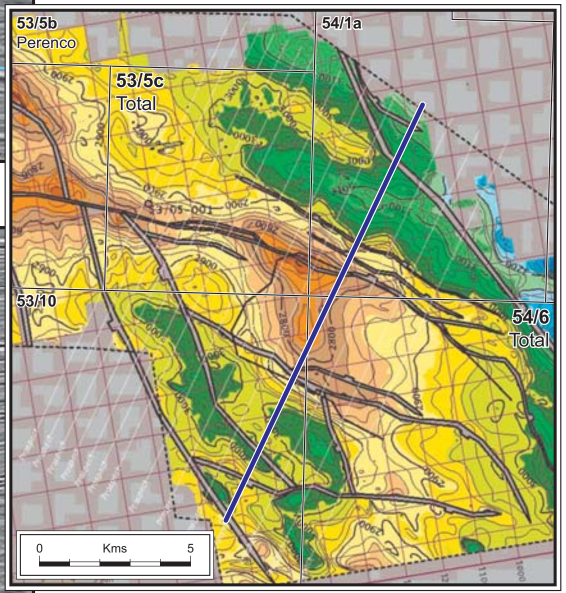


Figure 6.1

Top Dinantian Time Structure Map (ms)



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Top Dinantian Depth Map

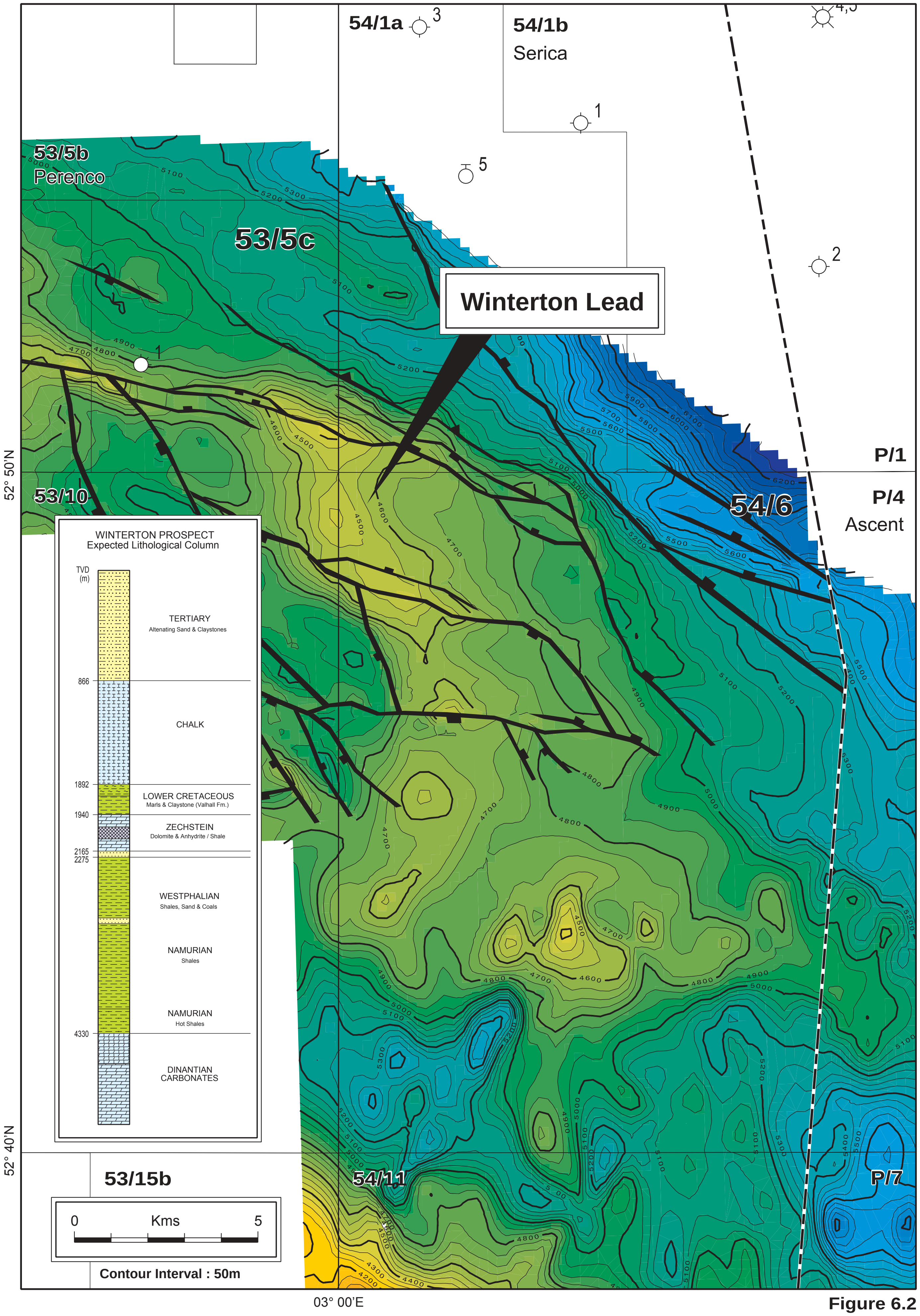

Figure 6.2

7 References

BESLY, B.M. 1998. Carboniferous. *In:* GLENNIE, K.W. (ed.) Petroleum geology of the North Sea, 4th Edition. Blackwell, Oxford, 104-136.

BOTT, M.H.P. 1987. Subsidence Mechanisms of Carboniferous Basins in Northern England. *In*: Miller, J., Adams, A. E. & Wright, V. P. (eds) *European Dinantian Environments.* John Wiley & Sons Ltd, 21–32.

CAMERON, T.D.J., CROSBY, A., BALSON, P.S., JEFFREY, D.H., LOTT, G.K., BULAT, J. & HARRISON, D.J.1992. The geology of the southern North Sea. *United Kingdom Offshore Regional Report*. HMSO for the British Geological Survey, London, 1-36.

CHADWICK,R.A.,KENOLTY,N.,WHITTAKER,A. 1983. Crustal structure beneath southern England from deep seismic reflection profiles. *Journal of the Geological Society* (London), **140**, 893-911.

COWARD, M.P. 1990. The Precambrian, Caledonian and Variscan framework to NW Europe. *In*: HARDMAN, R.F.P. & BROOKS, J. (eds.) *Tectonic Events Responsible for Britain's Oil and Gas Reserves*. Geological Society Special Publication, **55**, 1-34.

COWARD, M.P. 1993. The effect of Late Caledonian and Variscan continental escape tectonics on basement structure, Palaeozoic basin kinematics and subsequent Mesozoic basin development in NW Europe. *In*: PARKER, J.R. (ed) *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference.* Geological Society, London, 1095-1108.

FRASER, A.J. & GAWTHORPE. 1990. Tectono-stratigraphic development and hydrocarbon habitat of the Carboniferous in northern England. *In*: HARDMAN, R.F.P. & BROOKS, J. (eds.) *Tectonic Events Responsible for Britain's Oil and Gas Reserves*. Geological Society Special Publication, **55**, 49-86.

______2003. An Atlas of Carboniferous Basin Evolution in Northern England. *Geological Society Memoir*, **28**, 5-10.

FRASER, A.J., NASH, D.F., STEELE, R.P. & EBDON, C.C. 1990. A regional assessment of the intra-Carboniferous play of Northern England. *In:* BROOKS, J. (ed.) *Classic petroleum provinces.* Geological Society Special Publication, **50**, 417-440.

GLENNIE, K.W. (ed.) *Petroleum Geology of the North Sea,* 4th Edition. Blackwell, Oxford

GEORGE, G.T. & BERRY, J.K. 1997. Permian (Upper Rotliegend) syn-sedimentary tectonics, basin development and palaeogeography of the southern North Sea. *Geological Society, London, Special Publications*; **123**, 31-61.

GUTTERIDGE, P. 1995. Late Dinantian (Brigantian) carbonate mud-mounds of the Derbyshire carbonate platform. *Special Publications of the international Association of Sedimenologistst.***23**, 289-307

______1997. Dinantian depositional systems and exploration potential: offshore and onshore, The Netherlands. *Total internal company report.*

______2006. Dinantian sequence stratigraphy, burial history and dolomitisation of the onshore U.K. and S.N.S. *Total internal company report.* KK15349-R

HITZMAN, M.W. & BEATY, D.W. 1996. The Irish Zn-Pb-(Ba) orefield. *In:* SANGSTER, D.F. (ed). *Carbonate-hosted lead-zinc deposits*: Society of Economic Geologists Special Publication, **4**, 112-143.

KING, D.T. 1990. Probable influence of geography on the development and global distribution of Tournasian-early Visean age (Waulsortian and Waulsorian-like) mud mounds. *Journal of Geology*, **18**, 591-594.

LEEDER, M.R. 1976. Sedimentary facies and origins of basin subsidence along the northern margin of the supposed Hercynian Ocean. *Tectonophysics,* **36**, 167-179

LEES, A. 2006. Waulsortian *In:* DEJONGHE, L.(ed). Current status of chronostratigraphic units named from Belgium and adjacent areas, *Geologica Belgica*, Brussels, **9**/1-2: 151-155.

LEES, A., & MILLER, J. 1985. Facies variation in Waulsortian build-ups, Part 2; Mid-Dinantian build-ups from Europe and North America. *Journal of Geology*, **20**, 159-180.

MAYNARD, J.R., HOFMANN, W., DUNAY, R.E., BENTHAM, P.N., DEAN, K.P. & WATSON, I. 1997. The Carboniferous of Western Europe: the development of a petroleum system. *Petroleum Geoscience,* **3**, 97-116.

MONTY, C.L.V., BERNET-ROLLANDE, M.C. & MAURIN, A.F. 1982. Re-interpretation of the Frasnian classical 'reefs' of the southern Ardennes, Belgium. *Annals of the Geological Society of Belgium* **105**, 343-344.

SOPER, N.J., WEBB, B.C. & WOODCOCK, N.J. 1987. Late Caledonian (Acadinan) transpression in Northwest England: timings, geometry and geotectonic significance. *Proceedings of the Yorkshire Geological Society,* **46**, 175-192

SWANN, G. & GRAY, J. 2006. The hydrocarbon prospectivity of Britain's onshore basins. BGS report for the Department of Trade and Industry.

TSIEN, H.H.1985b. Algal-bacterial origin of micrites in mud mounds. *In:* TOOMEY, D.F. and NITECKI, M.H. (eds.) *Paleoalgology: Contemporary Research and Applications*. Springer-Verlag, Berlin, 290-296.

TUCKER, M.E., WRIGHT, P.V. 1990. Carbonate Sedimentology. Blackwell, Oxford, 225-227.

TURNER, J.S. 1949. The deeper structure of central and northern England. *Proceedings of the Yorkshire Geological Society,* **27**, 280-297.

VANDENBERGHE, N.1984. The subsurface geology of the Meer area in North Belgium, and its significance for the occurrence of hydrocarbons. *Journal of Petroleum Geology,* **7**, 55–66.