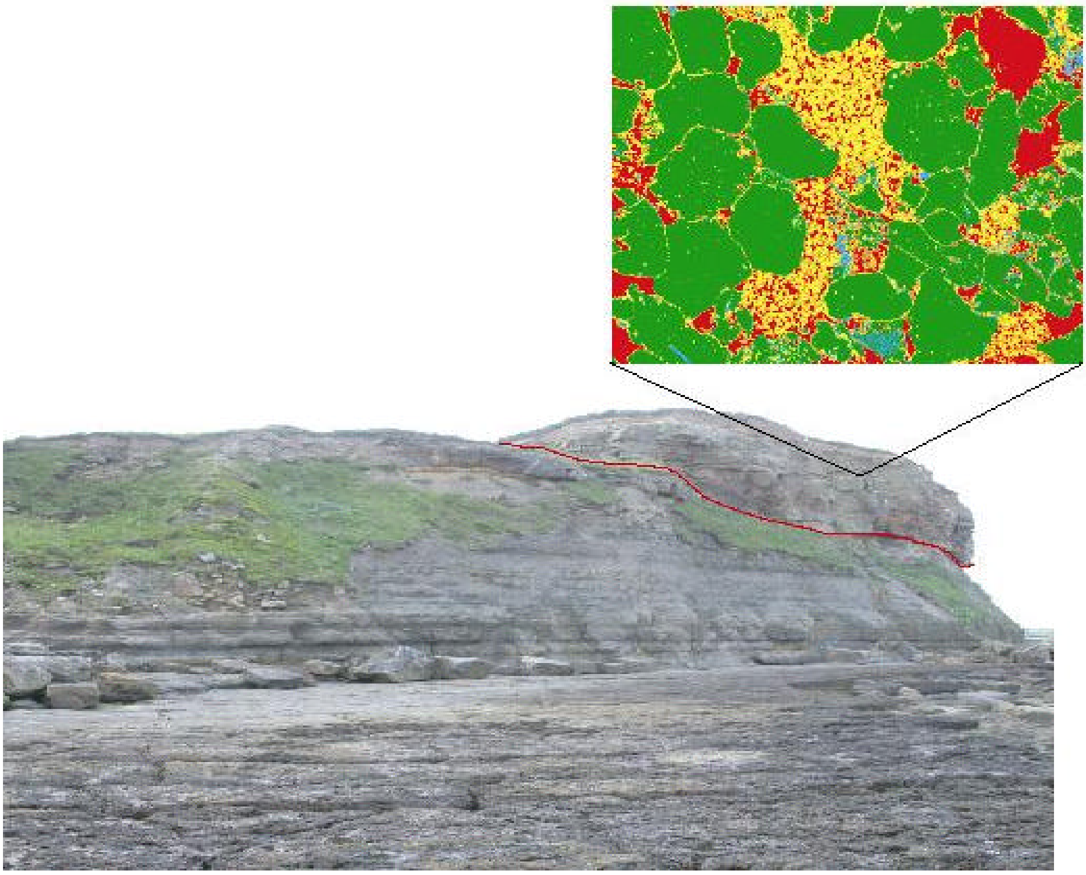
Reservoir quality of the Middle Jurassic sandstones (Ravenscar Group) along the Yorkshire coast



Christer B. Peltonen

Masters of Science Thesis in Petroleum Geology

Department of Geosciences, University of Oslo, Norway

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Front page pictures: Hundale Point just north Burniston Bay showing the horizontally lying marine Scarborough formation incised by a channel from the Scalby formation; SEM backscatter image with contrast intensity spectrum showing detrital grains (green), porosity (red) and pore-filling authigenic kaolinite (yellow).

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Chapter 1 Introduction

1.1 Purpose of Study

The Yorkshire coast provides one of the best places in the world to study Jurassic sediments. The relatively flat lying strata, and long uninterrupted sea cliff exposures allow for detailed studying and sampling. Of particular interest for this study, are the numerous Middle Jurassic sandstone units exposed at length along the Yorkshire coast between Ravenscar and Whitby. The contemporaneous nature of these sandstones to those found in the North Sea provides an invaluable resource for further developing the understanding of fluvial/deltaic reservoirs.

The main focus of this study is to exam and discuss the characteristic differences between the various sandstone facies found within the Middle Jurassic of Yorkshire, with relevance to reservoir potential; porosity, permeability, pore size distribution, communication, reservoir geometry, and the net to gross ratio of sand and shales (N/G). In addition, the degree of early diagenesis due to meteoric water flushing (leaching of potassium-feldspars and the precipitation of authigenic kaolinite) will be discussed and compared within the different depositional facies with respect to the effect on reservoir properties.

The Yorkshire coast provides a variety of sandstone facies; from lower-shoreface marine sandstones and crevasse splay sandstones to pure fluvial channel sandstones. The distribution and internal characteristics of these different sandstone facies can vary extremely, and it is important to understand these differences and how they affect the overall quality of a petroleum reservoir. This paper will compare, contrast and provide examples of the distribution and properties of these various sandstone facies, and discuss the possible implications on reservoir quality.

1.2 Location

1.2.1 Introduction

The area of research for this study was North Yorkshire, England (Figure 1.1). The sediments of interest accumulated in the Cleveland Basin, which forms the western margin of the North Sea Basin system (Rawson & Wright 1995). The Cleveland Basin is bounded to the west by the Pennine High, the south by the East Midlands Shelf, and to the north by the Mid-North Sea High (Figure 1.2).

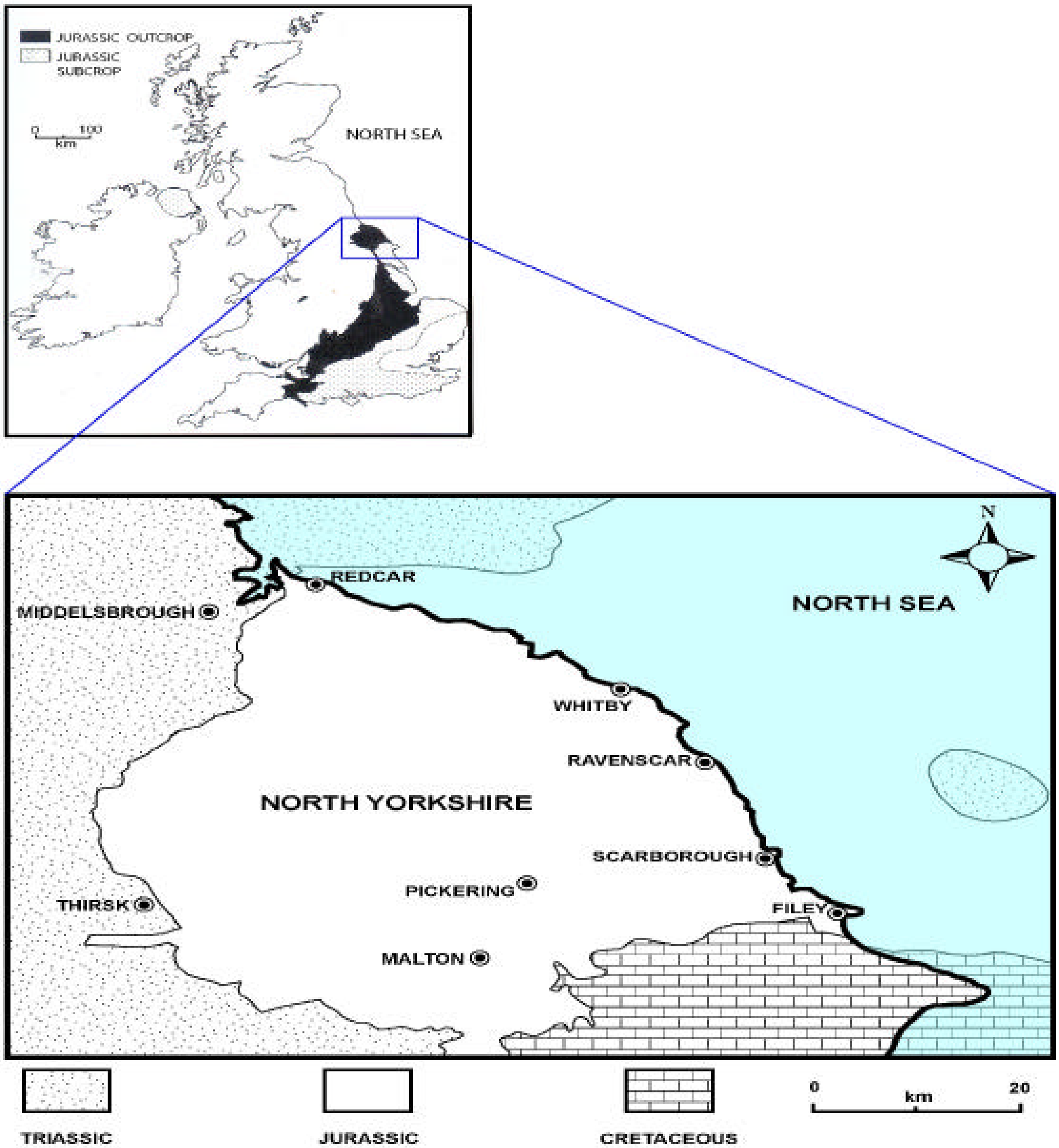


Figure 1.1. Basemap: Location of study area showing North Yorkshire and the Cleveland Basin.

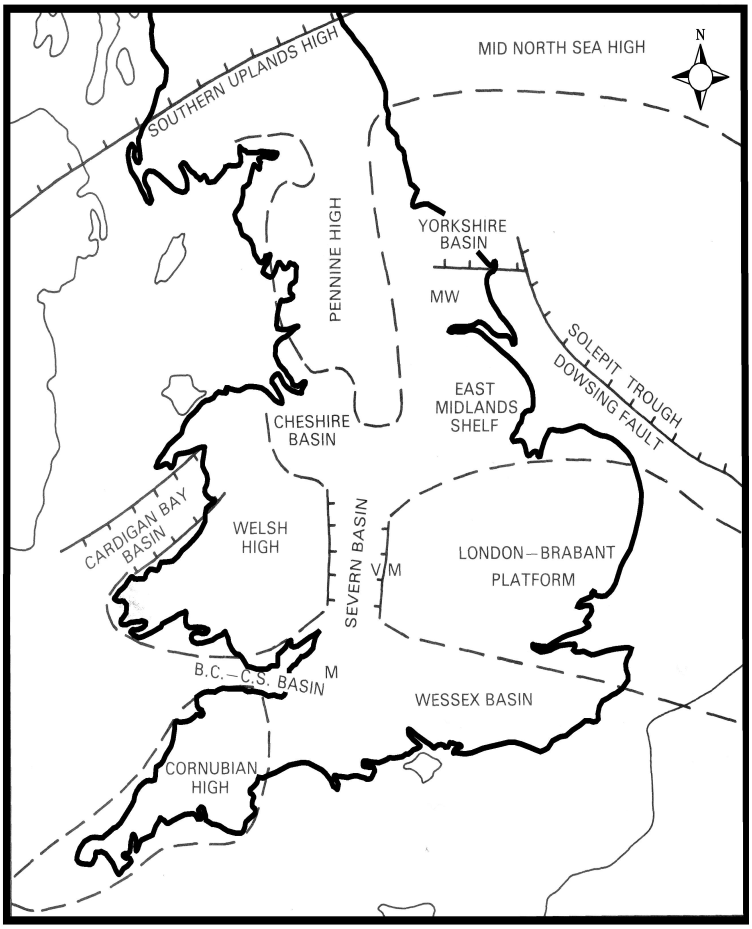


Figure 1.2. Principle structural features controlling Jurassic sedimentation (MW = Market Weighton; modified from Duff and Smith 1992).

Along a 65 kilometer stretch of coastline from Filey Brigg to Whitby, lie an almost continuous section of horizontally exposed rocks of the Jurassic. Included in these coastal exposures are the marine and non-marine deposits of the Middle Jurassic, which were the focus of this investigation. Specific sites of investigation of Middle Jurassic rocks were: Yons Nab, Osgodby Point, Scarborough-South Bay, Cromer Point, Long Nab, Hundale Point, Cloughton Wyke, Hayburn Wyke, and Whitby (Figure 1.3). All of these localities lie along the coast, within a short distance north and south of Scarborough. Below is a description of the above noted locations. The information provided in this introduction is brief, and only considers their basic geographic location, and the formations represented. More information will be provided in the later sections of this paper. The following description of localities begins south of Scarborough, and proceeds northwards to Whitby.

1.2.2 Yons Nab

Yons Nab is located approximately 6 kilometers south of Scarborough and is comprised of a gently westerly dipping succession of Middle Jurassic strata. Exposed in the cliffs and on the rock platform to the southeast of the Red Cliff Fault (Figure 1.4), are both marine and non-marine sediments of the Ravenscar Group. The uppermost unit is represented by the Scalby Formations Moor Grit Member, and the succession continues down through the underlying Scarborough Formation and the Gristhorpe and the Lebbertson Members of the Cloughton Formation. This is the type section for the Gristhorpe Member, Yons Nab Beds. The lowermost units represented at this location are of the Lebbertson Member which are exposed on the rock platform and form a broad break water reef (Figure 1.5).

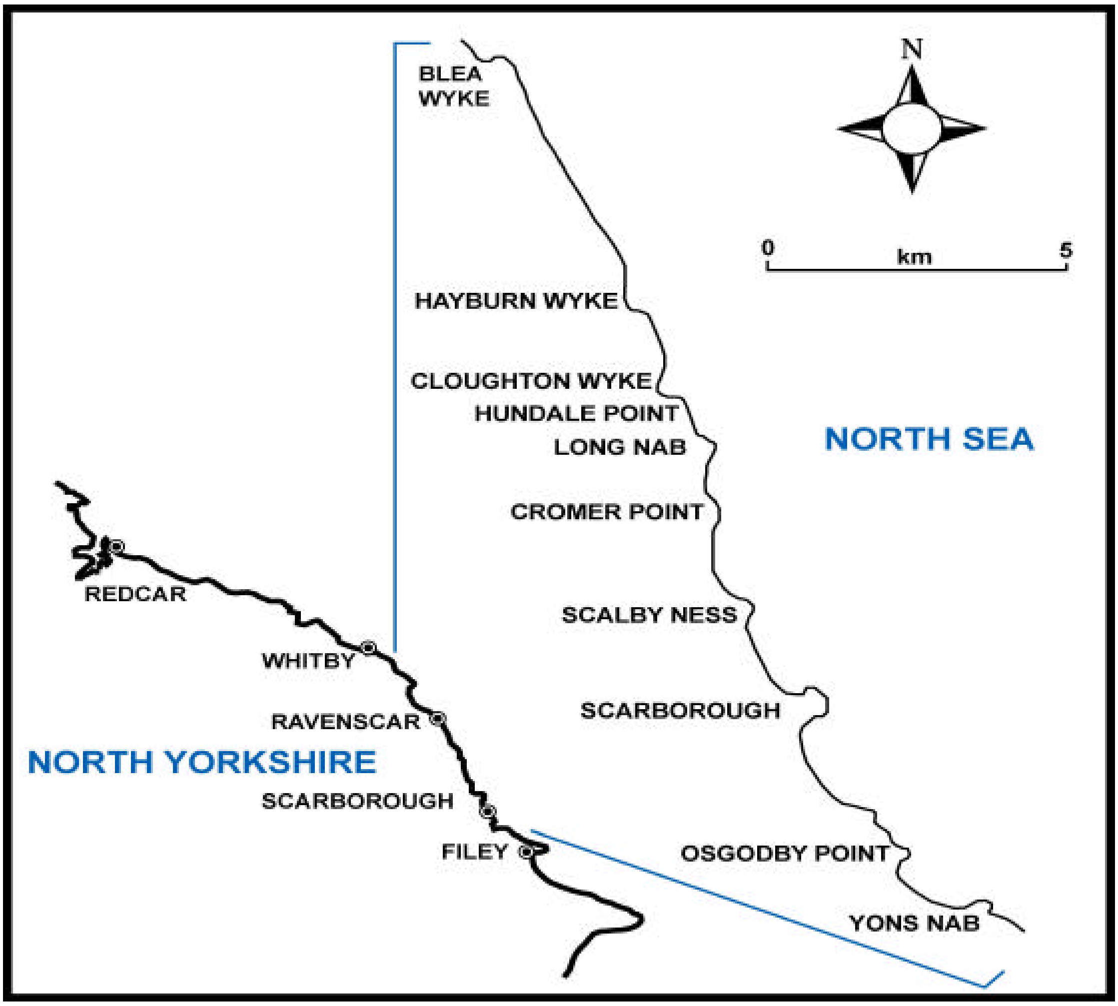


Figure 1.3. Coastal -section with outcrop localities mentioned in text.

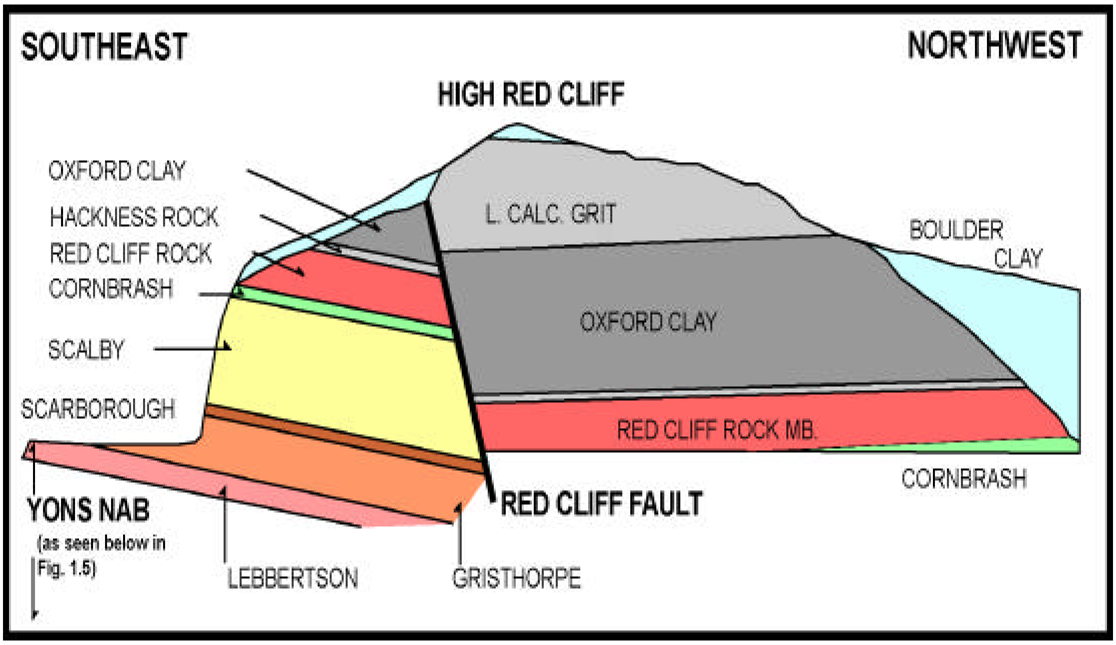


Figure 1.4. Cross section of cliff-face exposed at south end of Cayton Bay, just north of Yons Nab (modified from Rawson & Wright 1995).

Figure 1.5. Coastal outcrop of Lebbertson Member at Yons Nab.

1.2.3 Osgodby Point

Located south of Scarborough approximately 3.5 kilometers is the investigated locality of Osgodby Point (Figure 1.6). At this location, the eastern branch of the Cayton Bay fault cuts through the headland of Osgodby Point and brings the Millepore Bed of the Lebbertson Member up to form a natural barrier protecting the headland. Overlying this resistive rock platform is a thin sequence of the marine Yons Nab Beds, and some strongly cross-stratified channel sands from non-marine Gristhorpe Member. All of the members represented at this location are included within the Cloughton Formation.

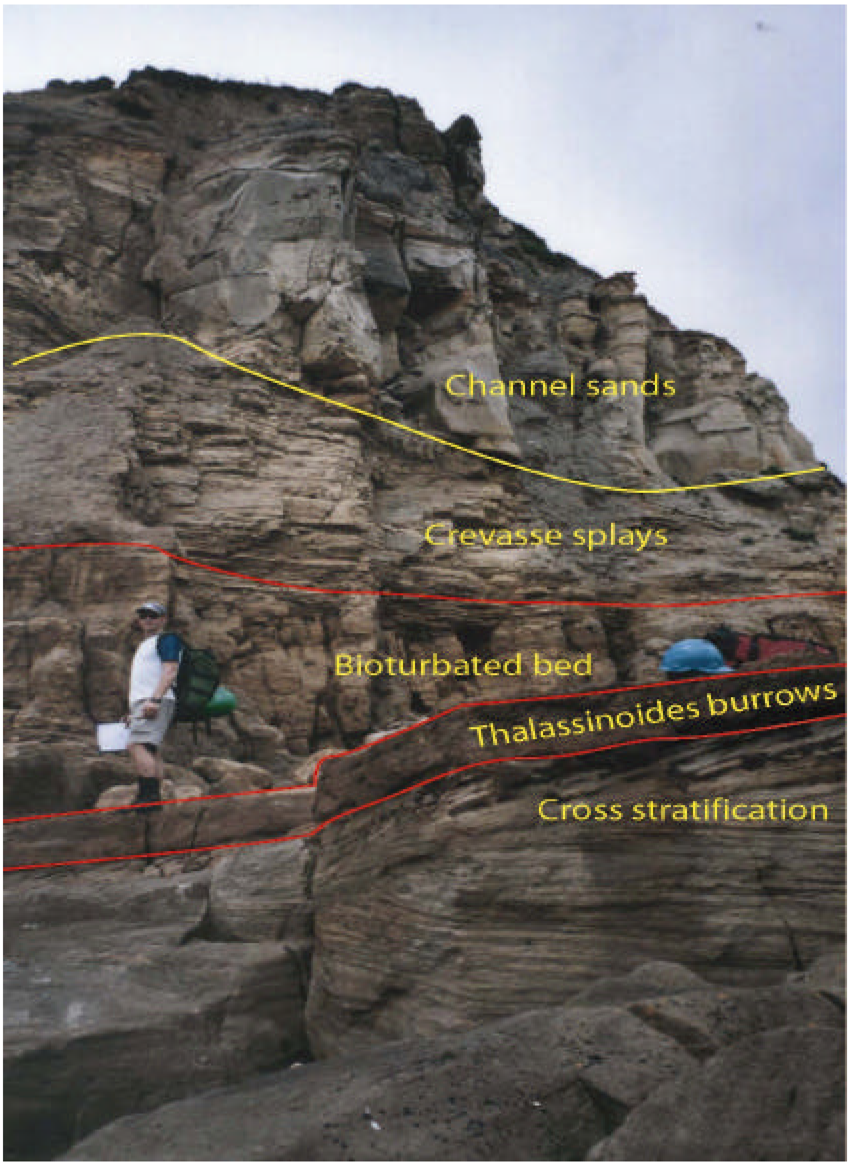


Figure 1.6. Osgodby Point and sedimentary features of the Cloughton Formation.

1.2.4 South Bay

The South Bay of Scarborough stretches approximately 2 kilometers southwards to White Nab. Exposed at this location are channel sands from the Moor Grit and Long Nab Members of the Scalby Formation, which overlay, and commonly incise into the underlying marine members of the Scarborough Formation. The formations found at the South Bay locality represent the uppermost formations within the Ravenscar Group.

1.2.5 Cromer Point - Long Nab - Hundale Point

These localities lie just north of Scarborough, and occur along the 4 kilometer stretch of coastline from Scalby Ness to Hundale Point (Figure 1.7). These localities are grouped together because they are composed almost entirely of Scalby Formation deposits; the Moor Grit and the overlying Long Nab Members. The underlying marine Scarborough Formation can be observed at Hundale point, where it is commonly incised into from the overlying channel sands of the Moor Grit. Like the previously noted location of South Beach, this stretch of coastline represents the uppermost formations of the Ravenscar Group.

1.2.6 Cloughton Wyke - Hayburn Wyke

Cloughton Wyke lies approximately 5 kilometers north of Scarborough, with Hundale Point immediately south, and Hayburn Wyke 3 kilometers to the north. The stratigraphy is slightly tilted towards the south in this area, and walking north along the coast will take you down section from the Scarborough Formation to the lower most formation of the Ravenscar Group, the Saltwick Formation (Figure 1.8). The cliffs at the southernmost point of Cloughton Wyke are dominated by the marine deposits of the Scarborough Formation. Northwards into the center of Cloughton Wyke are the underlying non-marine and quasi-marine (Rawson & Wright 1992) deposits of the Gristhorpe Member. Northwards from Cloughton Wyke, the stratigraphy continues to move down section through the Ravenscar Group: This includes the Lebbertson Member of the Cloughton Formation, the Sycarham Formation, the Eller Beck Formation, and the lowermost Saltwick Formation.

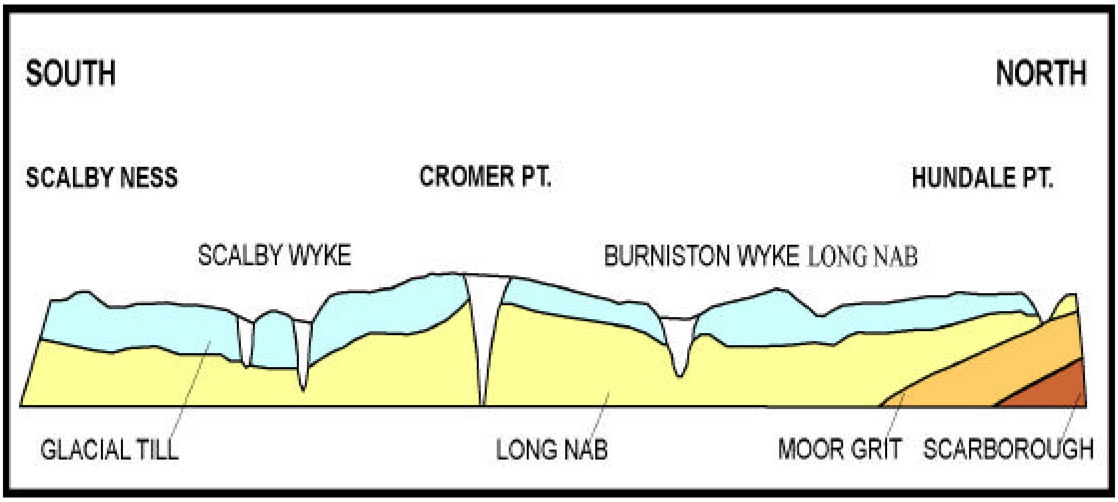


Figure 1.7. Cross-section from Scalby Ness to Hundale Point.

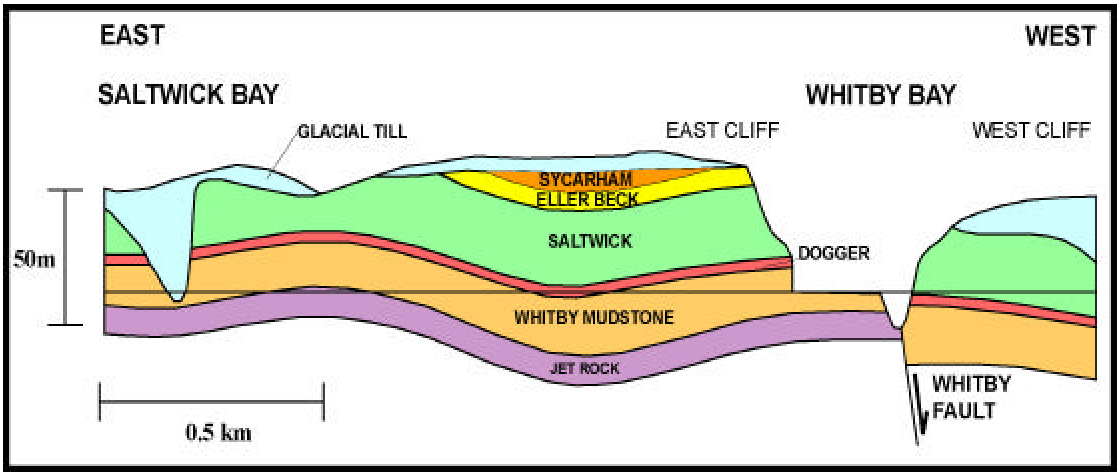


Figure 1.8. Cross-section from Saltwick Bay to Whitby Bay.

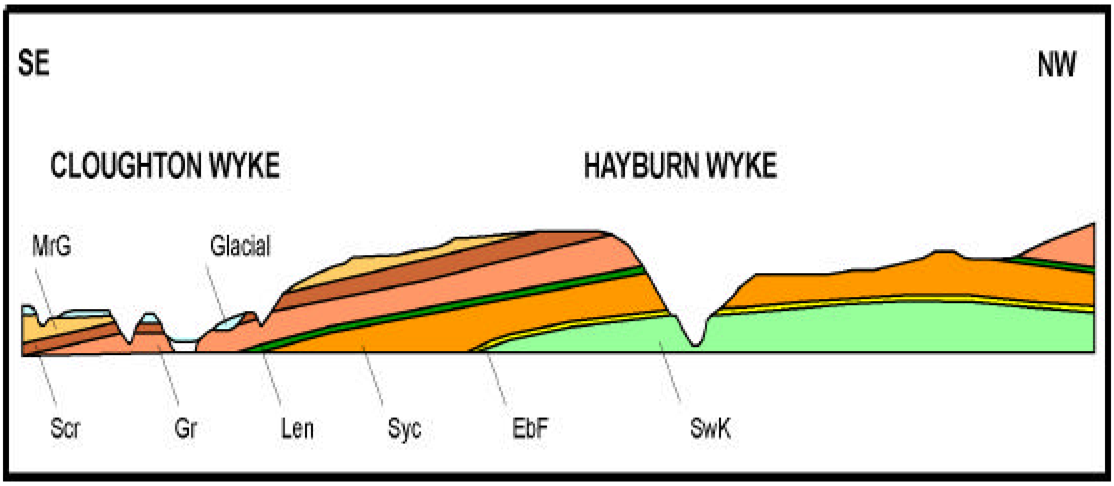


Figure 1.9. Cross-section stretching from Cloughton Wyke to Hayburn Wyke.

1.2.7 Whitby

Whitby is located approximately 40 kilometers to the north of Scarborough. This location includes deposits from the Lower Jurassic (Whitby Mudstone Formation) to Middle Jurassic (Eller Beck Formation). The town of Whitby is transacted by a north-south striking, normal fault. This fault separates this location into Whitby east, and Whitby west (Figure 1.9). Whitby west is primarily composed of stacked-channel sand deposits of the Saltwick Formation (Figure 1.10). In contrast, the eastern side of the fault is represented primarily by level-bedded, overbank deposits. These depositional differences will be discussed later.

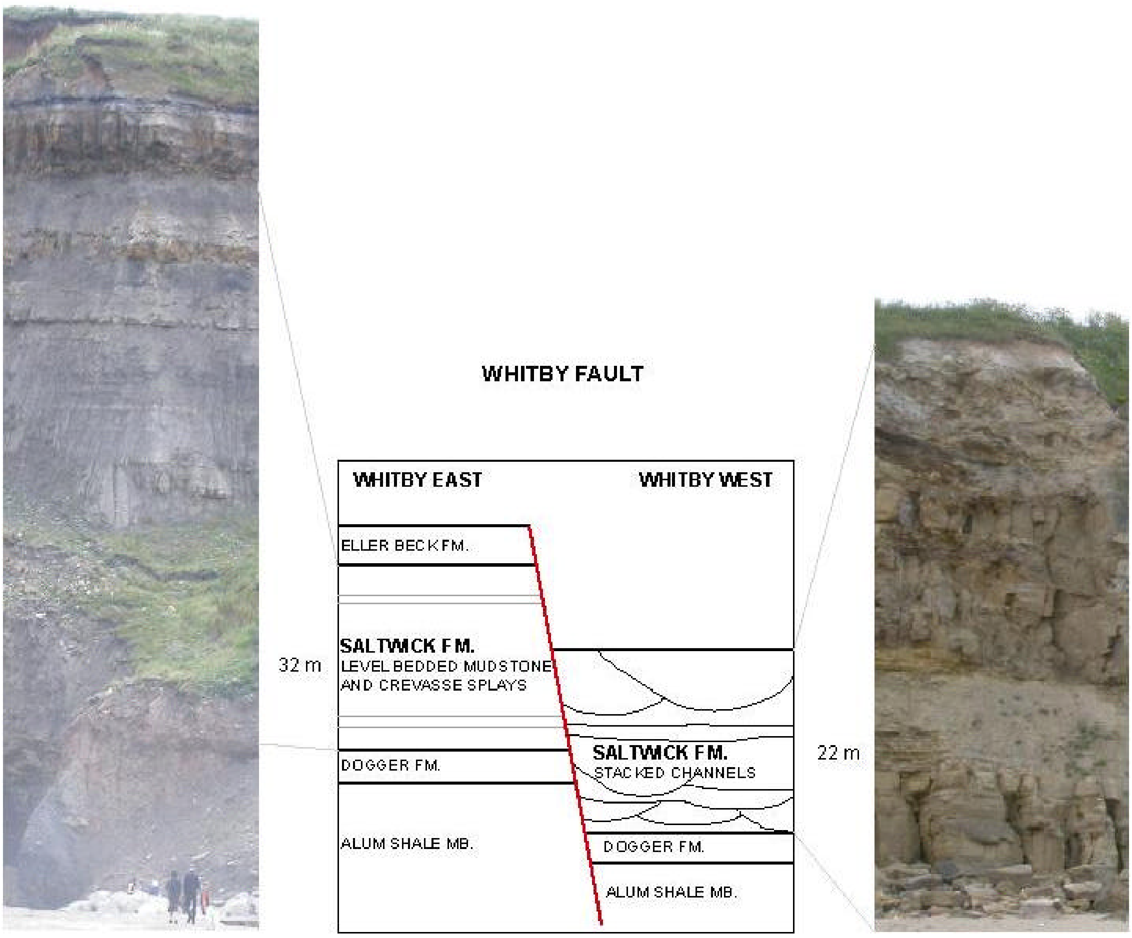


Figure 1.10. Whitby fault showing the difference in deposition within the Saltwick formation; note that stacked-channels only occur on the west side of the fault whereas the east side is dominated by flat-lying mudstones and crevasse splay deposits. Total offset approximately 12 meters.

Chapter 2 Geological Framework

2.1 Introduction – Geologic Framework

The Yorkshire coast provides some of the most impressive exposures of Jurassic rocks found in the World. They are virtually flat-lying and almost continuously exposed along the rugged cliffs of this wave dominated coastline. The resistive nature of these channel sandstone units has led to their unique preservation, commonly as thick prominent headlands, and allows them to be studied in high detail. The Jurassic of Yorkshire is dominated by marine sequences, but within the Middle Jurassic there occurred a period of uplift which produced a series of regressive events and led to the deposition of some fluvio-deltaic sequences (Cope 1995). This Middle Jurassic sequence of Yorkshire is approximately 250 meters thick, and composed of the above mentioned fluvio-deltaic sediments; sandstones, siltstones, shales and minor coals, deposited within a series of marine sequences . The deposition of this 'deltaic series' is an onshore continuation of the offshore geology of the Sole Pit Basin, and is therefore vital in the study of regional Middle Jurassic sediments.

2.2 History of Geologic Studies in Yorkshire

Substantial work within geology and its related disciplines has been completed along the Yorkshire coast. This is due to a variety of factors, but historically the main driving force can be attributed to the basic attraction to the beautiful landscape of which the Yorkshire coast offers. The natural settings of Yorkshire provided naturalist, fossil collectors and geologists alike with a wonderland of well exposed, fossil-rich, flat-lying strata. This area inspired some of England's and Europe's most renowned geologist to further develop the foundations of modern geology.

Economic interest also had an undeniable influence on the vast amount of work which has been completed in and around Yorkshire. The Industrial Revolution, and its basis coal, led to geologic exploitation and an increased interest in Yorkshire geology. World War I and II increased the demand for both coal, and iron-ore, which in turn created incentives for a greater geological understanding of the area. Most recently, the discovery of oil in the North Sea inspired a new wave of interest, and financial support for research in the Yorkshire area. Also of great interest is the similarity between the Middle Jurassic sandstones of Yorkshire (Ravenscar Group) with those of the Middle Jurassic sands of the northern North Sea Basin (Brent Group). The Ravenscar Group sands of Yorkshire are not only the key to understanding the offshore geology of England, and its potential for hydrocarbons, but it also provides an invaluable resource for the better understanding of the North Sea Basin, Brent Group reservoir sandstones.

Geologic research in the Yorkshire area stretches as far back as the beginning of the 19th century. This coincided with the literary and philosophical movements which centered themselves in towns such as Whitby, Scarborough, and York (Hemingway 1974). The Yorkshire Philosophical Society was established in 1820’s, and in 1823 they founded a geology museum in York. This created the basis, and driving force behind geologic interest and studies within the Yorkshire area. John Phillips, the nephew and student of William Smith was appointed keeper of the Yorkshire Philosophical Society’s museum in York, and later made significant contributions to the understanding of Yorkshire Geology (Illustrations of the Geology of Yorkshire: Part I – The Yorkshire Coast, 1829, 1835, 1875). One of the earliest comprehensive studies was that of Reverend George Young and John Bird who published A Geological Survey of the Yorkshire Coast, in 1822. Ironically, the most famous of the Yorkshire Geologist, William Smith, published very little with regards to Yorkshire geology. This was limited to the four sheets of his map of Yorkshire (1821), a map of the Hackness area, and a Memoir on the Stratification of the Hackness Hills (published in1892 by Fox-Strangways). Although his publications were of small influence, he became a very prominent and respected figure in 1831 when the Geological Society of London awarded him with the first and very prestigious Wollaston Medal.

These early publications from the above mentioned individuals, created the foundation for future researchers, which further developed the knowledge of Yorkshire’s geology, and inspired future geologist to expand upon these findings.

During the middle to late 19th century, the Geological Survey of Great Britain undertook the task of mapping Yorkshire County. The side effect of this was the production of private memoirs and publications that sprang up from those individuals involved in the field mapping project. Specifically relevant to East Yorkshire was the work completed by Fox-Strangways (Jurassic Rocks of Britain, 1892). His work is still considered today as one of the standards for north-east Yorkshire (Taylor 1974). Fox-Strangways applied his newly acquired data to that of the previous workers (i.e. Phillips, 1829) and began to describe and apply the concepts of depositional environments. Fox-Strangways (1892) interpreted the Ravenscar Group as an estuary type depositional setting, and defined it as the Estuarine Series. He further divided the three major non-marine units (Saltwick, Cloughton, and Scalby Formations) into Lower, Middle, and Upper Estuarine Series. This interpretation and classification influenced the successors of Fox-Strangways to further develop his ideas. Kendall and Wroot (1924), and Black (1928, 1929) began to refer to these estuarine sequences as deltaic, which influenced future work and led to the subsequent revision of Fox-Strangways Estuarine Series to that of the Deltaic Series, defined by Hemingway (1949). Hemingway interpreted the Ravenscar Group as a 'predominantly marshy deltaic environment repeatedly flooded by the sea' (Rawson & Wright 1992, p182). The concept and nomenclature of Hemingway's original Deltaic Series was further revised to conform to new standards in Hemingway and Knox (1974).

Following the above noted foundation-forming geological research, a series of more detailed, comprehensive studies were undertaken. These have been focused mainly on the further interpretation of depositional environments (Sequence Stratigraphy, Geomorphology, Palynology), and a variety of studies related to the Brent Group. As mentioned previously, the discovery of oil in the North Sea, and the close similarity between the Brent and Ravenscar Groups, led to an increase in interest and funding for research in the Yorkshire area. Work related to these nearly contemporaneous sandstones began some 25 years ago and was spear-headed by the likes of Nami and Leeder (1979), Livera and Leeder (1981), and Hancock and Fisher (1981 and 1985).

The history of geologic research in Yorkshire has deep roots that stretch back as far as the early 1800's and it includes contributions from numerous individuals which go beyond the scope of this paper to be discussed. A summary of these individuals and their contributions is listed in Sheppard (1915), and Taylor (1974).

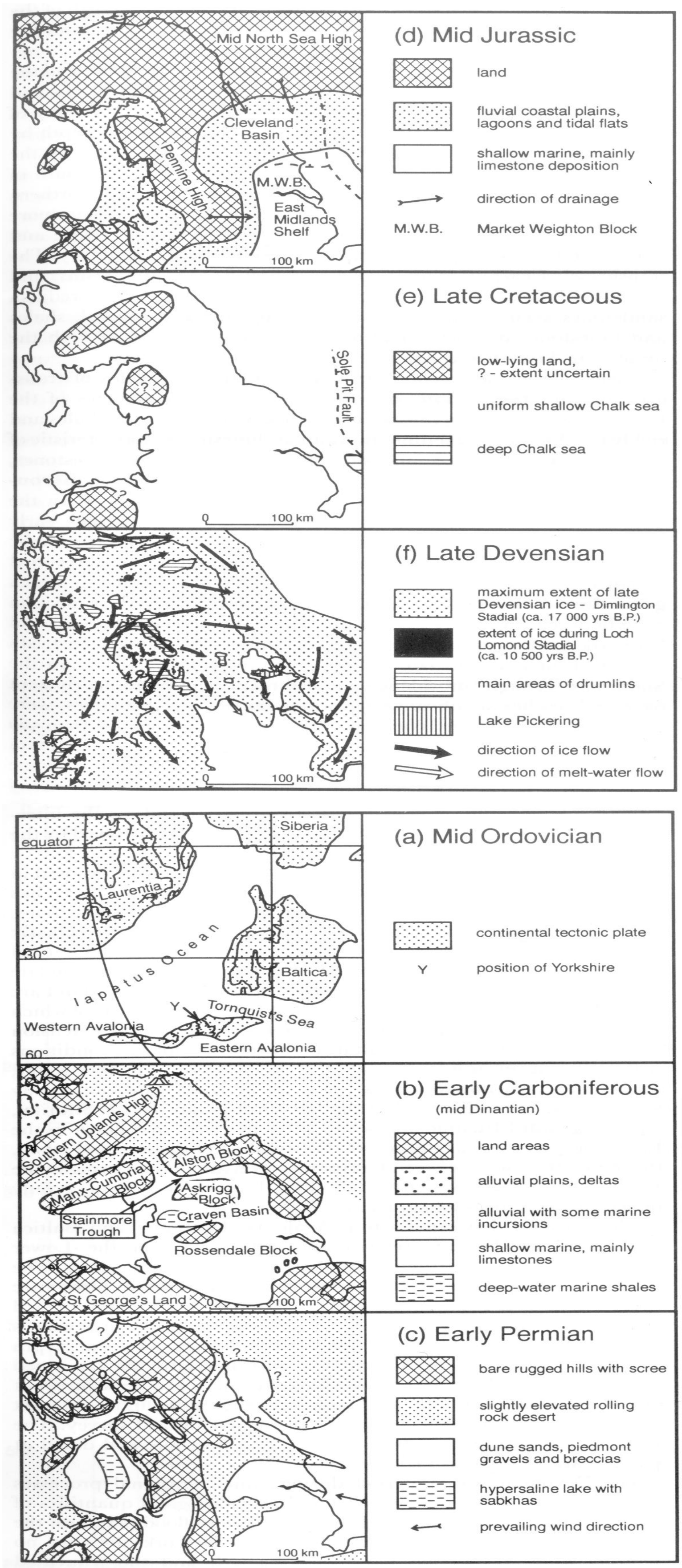


Figure 2.1. Palaeogeographic maps showing relative plate movement of the Yorkshire area from Early Permian through Middle Jurassic (Scrutton, 1996 p.12).

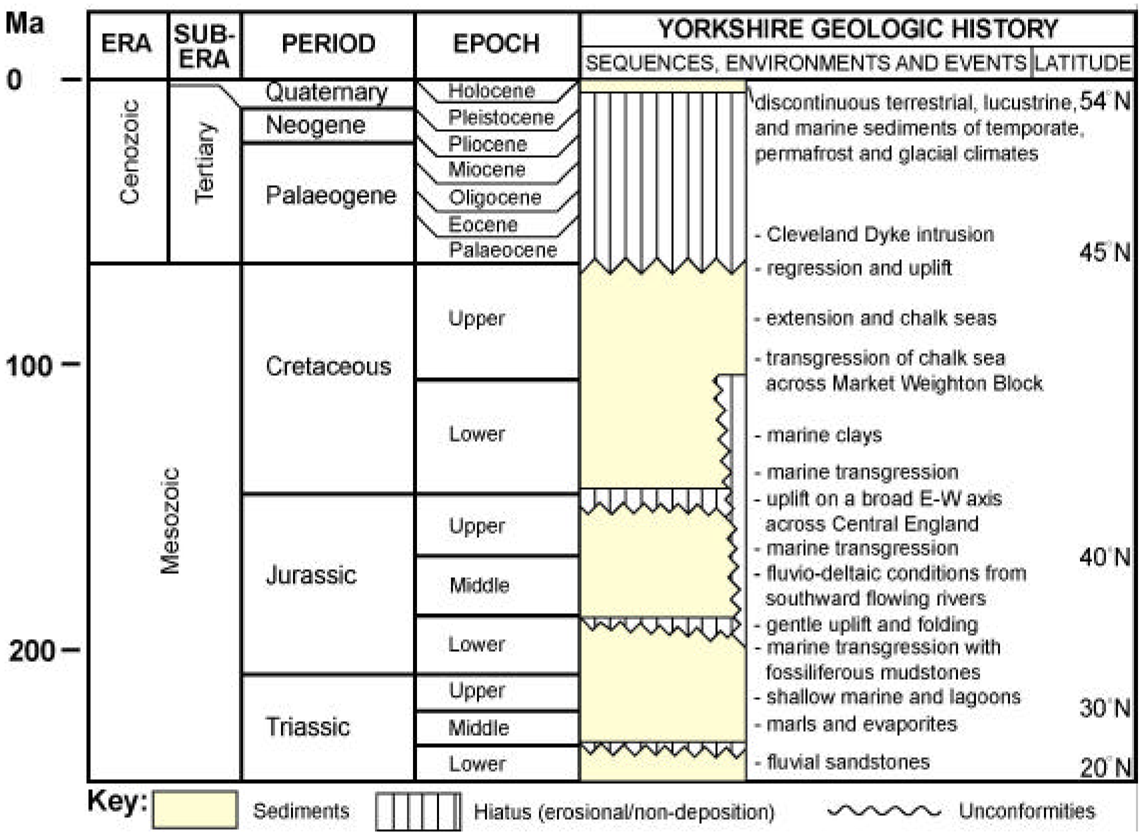


Figure 2.2. Depositional history summary of Yorkshire (Modified from Scrutton, 1994)

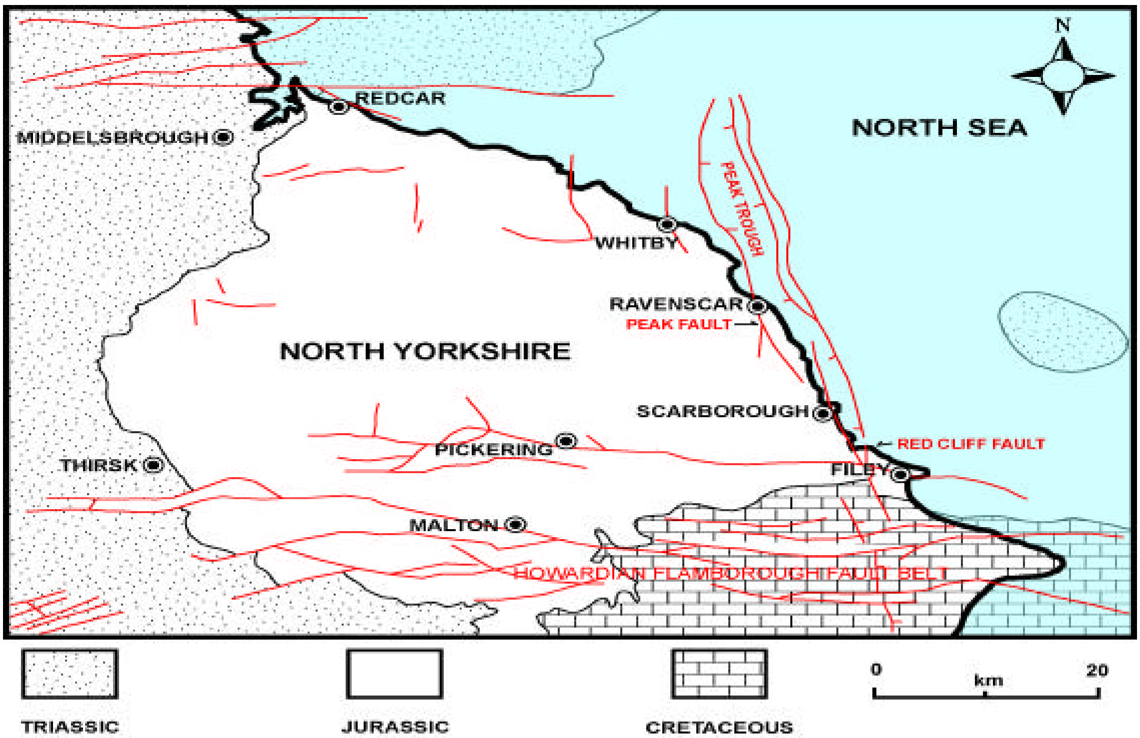


Figure 2.3. Structural map showing faulting pattern in North Yorkshire (Modified From Rawson&Wright, 1992)

2.3 Structural Evolution and Paleogeography

Previous to the Caledonian Orogeny, the area of Yorkshire was located on the northern margin of the micro-continent Eastern Avalonia. Throughout the Ordovician and Early Silurian, Eastern Avalonia was located just south of the equator, and moving northwards towards the paleo- continents of Baltica and Laurentia (Figure 2.1a). The consequent collision of these paleo-continents, in the early Devonian, would initiate the Caledonian Orogenic cycle. Consistent with other parts of Europe, the Caledonian Orogeny culminated in the compression and deformation of the Lower Palaeozoic rocks of Northern England. These pre-Caledonian rocks were tightly folded and erosional processes removed much of the uplifted relief. The sediments produced during this uplift and erosion were deposited in the intermontane basins to the south, but in the Yorkshire area, there is an unconformity correlated to this period. The folded Lower Palaeozoic rocks of Yorkshire are directly overlain by sediments of the Early Carboniferous, and form a widespread angular unconformity. A summary of the depositional history, including the timing of unconformities, information on depositional environments, events and latitude is presented in Figure 2.2. Another very important by-product of the Caledonian Orogeny was the generation of granite magmas. It is interpreted (Hemingway 1974), that these deep magmas were injected as plutons into the shallow sediment packages, which greatly influenced the topographic relief of northern England, and played a significant role in the later development of the Cleveland Basin, i.e. The Market Weighton Block.

The effects of the Caledonian Orogeny began to diminish by the onset of Late Devonian and a period of crustal extension prevailed. This ‘post-Caledonian crustal extension broke up the eroded roots of the Caledonian mountains into a series of relatively buoyant blocks and subsiding half-graben basins that still influence the topography of northern England today’ (Scrutton 1996, p 14). The onset of the Carboniferous is associated with a period of transgression, and the deposition of sediments into a block and basin topography. Sedimentation continued throughout most of the Carboniferous, which was dominated by cycles of transgression and regression. The lower most Carboniferous (Dinantian) can be divided into six mesothem cycles (Scrutton 1996). The transgressive phases of these cycles are represented by calcareous shales and tropical limestone, whereas the regressive phases by oolitic limestones, dolomites, and fluvial sandstones. These mesothem cycles of deposition produced a distinguished pattern of minor sedimentary cycles which are classically known as the well developed Yordale facies. These minor sedimentary cycles are comprised of a series of marine limestone, succeeded by shale, sandstone and coal. The Yordale facies continued through to the Namurian, but was rapidly displaced by the southward progradation of thick, coarse grained fluvial and deltaic sandstones (Millstone Grit) which infilled the previous basin and block topography. Towards the end of the Carboniferous, in Westphalian times, transgressive events became less marked, and fluvial/deltaic deposition declined. This allowed greater development of soil horizons and swamp vegetation, and culminated in the deposition of thick coal seams. These Coal Measures reach a thickness of up to 1500 meters, and are consistent with the Late Carboniferous tropical coal belt which stretched from Eastern Europe to Eastern U.S.A. They are outcropped along the Leeds-Sheffield industry belt, and have been of enormous economic influence. In addition to the vast Coal Measures, the Westphalian deposits also include numerous laterally inconsistent sand bodies which form major hydrocarbon reservoirs in the East Mid-lands area (Kirby et. al. 1987). The end of the Carboniferous period brought about the Variscan Orogeny, and its associated gentle folding, extensive faulting, and uplift. Yorkshire was then part of the broad Pennine Basin, north of the rising land mass produced by the Variscan Orogeny. The uplift and erosion produced by this orogenic event led to the infill of the Pennine Basin with cyclical continental red-beds. Uplift and subsequent erosion would lead to the removal of hundreds of meters of sediment, and the area of Yorkshire would be reduced to a low, gently undulating peneplane (Kent, 1980). This period of compression and subsequent inversion would also lead to the development of a series of anticlinal structures. The majority of deformation was concentrated in the former shale filled basins (Kent, 1980), in addition to the simple reactivation of listric, normal growth-faults (Kirby et. al. 1987). An important product of this period of compression was the development of the Pennine Anticline, which delineates the Cleveland Basin to the west, and served as a major controlling factor in future depositional patterns.

At the onset of the Permian Period, Yorkshire was located in the heart of the ‘dry-belt’, at approximately 13° north. It was part of a broad, gently subsiding shelf, and was comprised of the above mentioned low-lying Late Carboniferous peneplane. Desert conditions were dominant, and the deposition of dune sands by easterly winds ensued (Rotliegend equivalent). These are associated with piedmont breccias and gravels, and lie erosively and unconformably upon the Carboniferous peneplane. The eolian conditions persisted to the beginning of the Upper Permian, where continued subsidence finally led to the rapid flooding of the basin. The transgression of the Zechstein Sea caused a partial reworking of underlying eolian sediments, and the initiation of widespread marine and hypersaline conditions. The Zechstein Sea occupied a vast amount of area, extending continuously from the Pennines across the North Sea and much of northern Europe (Kent, 1980). Due to periodic recharge from normal marine waters, the salinity levels in the Zechstein Sea varied greatly. This led to a diverse amount of sediment types, and depositional cycles. In Scrutton 1996, there are four major cycles defined: They consist of limestone (dolomites) succeeded by evaporates (gypsum/anhydrite, halite, and potash). This trend of cyclical salinity driven deposition continued through to the end of the Permian, where the deposition of continental 'red-beds' ensued and gradually filled the basin. These sediments came from westward areas of relief, and were comprised of red sandstones, siltstones and mudstones. The deposition of these continental clastic-sediments persisted through the Permian-Triassic boundary and was not interrupted until marine waters transgressed the area in the Late Triassic (Rhaetian). This transgressive event represents the beginning phase of a major sea level rise, and/or a period of local subsidence, and led to broad open marine conditions which would persist into Lower Jurassic.

Subsidence of the Yorkshire area was initiated at the beginning of the Permian and continued through into the Mesozoic. Towards the end of the Triassic, the Cleveland Basin began to develop through differential subsidence, but was still not an independent, well defined basin (Rawson & Wright 1992). It wasn't until the beginning of the Jurassic Period, when the structural feature of the Market Weighton Block had formed, that a distinct Cleveland Basin was formed. The Cleveland Basin was now well delineated; to the west and northeast by less subsident blocks which formed the Pennines and Mid-North Sea High; to the south by the Market Weighton Block; and to the east by the Sole Pit Trough.

The Market Weighton Block was part of the East Midlands Shelf, and formed a regionally important structural feature. It was originally described as a simple anticlinal structure produced during Variscan compression (Kendall 1905; Arkell 1933), but later with the help of seismic data, it would be regarded as a product of a deeply buried granite block which remained buoyant throughout the Jurassic and Cretaceous Periods (Sellwood & Jenkyns 1975; Kent 1980). The Market Weighton B lock acted as a hinge between the shelf and the basin, and its differential subsidence and/or uplift greatly influenced the thickness of Jurassic strata.

Faults and fault timing are not completely understood within the Cleveland Basin, but some evident patterns do exist. There is a general pattern of north-south and east-west faulting (Figure 2.3). The north-south oriented normal faults were active within the Cleveland Basin from Triassic to Late Cretaceous. This fault activity was concentrated along the coastal Peak Trough and its related parallel structures (Peak Fault and Red Cliff Fault). The east-west faulting was concentrated within the Vail of Pickering, and was active from Late Jurassic to Cretaceous (Kirby et. al. 1987).

By the beginning of the Jurassic, the Yorkshire area was located at approximately 40° north of the equator, and a large scale transgression had almost completely engulfed the Cleveland Basin (Scrutton 1994, Figure 2.4). In addition to the transgressive conditions in Early Jurassic, the Cleveland Basin continued to subside rapidly and resulted in the deposition of 420 meters (maximum thickness) of Lias sediments. Distribution of these Lias sediments can be seen in the isopach map below (Figure 2.5). This sequence was entirely marine and consisted of dominant siliciclastic, fossiliferous mudstones, with related shallow marine sandstones and ironstones as well as occasional calcareous intercalations. These widespread open marine conditions prevailed through to the beginning of the Middle Jurassic.

In the end of the Lower Jurassic (Toarcian) a period of volcanic activity was initiated within the Central North Sea resulting in a period of regional uplift and gentle folding. This led to the end of the widespread marine conditions, and introduced a period of dominant fluvial/deltaic conditions. This uplift created increase relief of the Mid-North Sea High and subsequently large amounts of sediments were eroded and redistributed by southward flowing rivers into the Cleveland Basin. Although this period was dominated by non-marine deposition, there were three marine sequences which separate these fluvial/deltaic sediments into four distinct packages. These marine incursions within the Middle Jurassic sequence were probably short lived and overall evidence suggests that a relatively rapid development of small prograding deltas and subsequent alluvial plain conditions prevailed (Rawson & Wright 1992). This fluvial/deltaic system would continue until late Middle Jurassic (Bathonian-Callovian), where a transgression ensued and once again engulfed the area in marine conditions. This marine incursion transgressed into the Cleveland Basin from the East and variety of marine sandstones, shales, and limestones of the Cornbrash formation were draped over the underlying fluvial deposits of the Scalby Formation. Although marine conditions persisted through to the end of Kimmeridgian times, the Late Jurassic was affected by rifting and fault block rotation which broke up the deposition of a predominant mudstone facies. These mudstones of the Oxford Clay were widespread inland and to the south of the Cleveland Basin, but locally (adjacent to the Market Weighton High) they were displaced by a variety of limestones, corals, and calcareous sandstones (Lower Calcareous Grit, Coralline Oolite, and Upper Calcareous Grit Formations). Despite these local variations the transgression continued and reached a maximum at the Oxfordian-Kimmeridgian boundary. By this time the deposition of marine clay facies prevailed, and the Ampthill Clay and Kimmeridge Clay formations were deposited across the entire Cleveland Basin. The Kimmeridge Clay was by far the most widespread and uniform of all of the Late Jurassic sediments, and it extended laterally into the adjacent North Sea Basin, where it serves as the areas primary source rock.

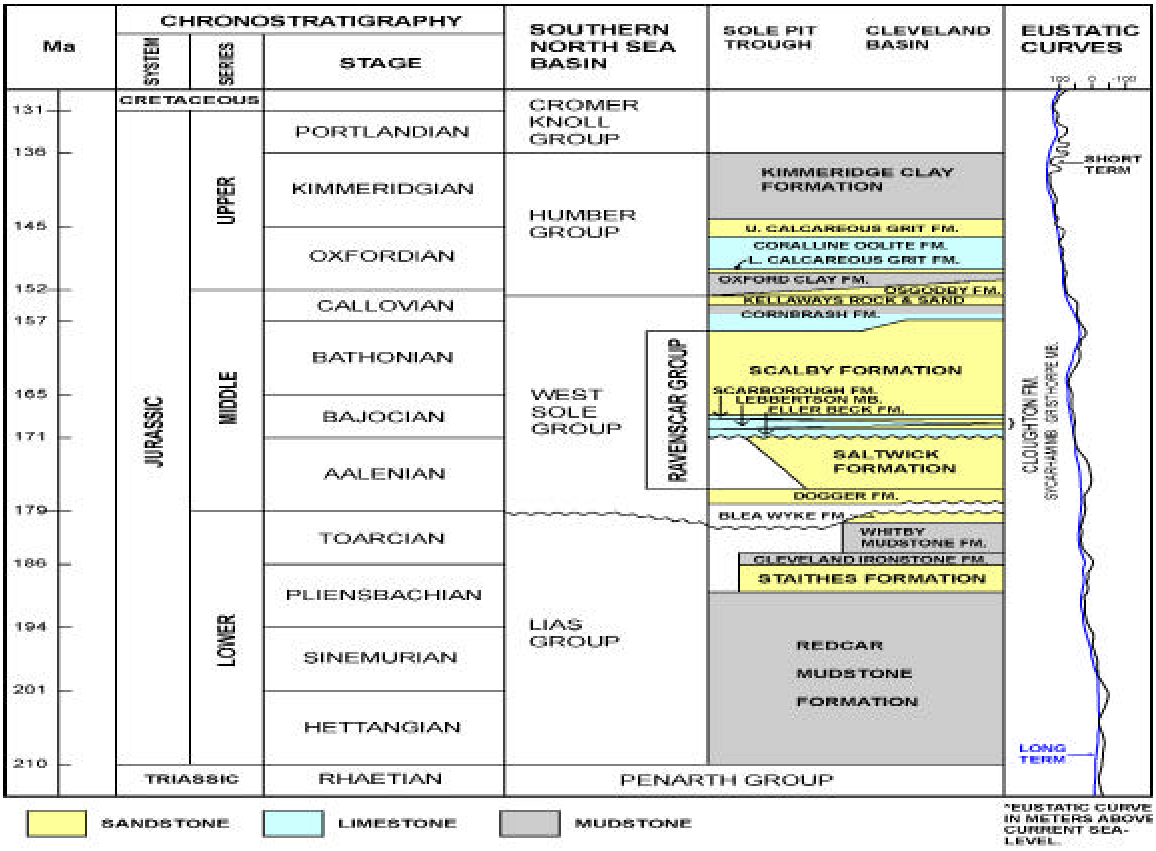


Figure 2.4. Chronostratigraphic chart showing depositional sequences and relative sea level (Modified from Cameron et. al. 1992).

From the end of the Late Jurassic to the beginning of Early Cretaceous, the Cleveland Basin experienced a period of inversion (rifting). This occurred along a broad east-west axis which stretched across the entire region from Central England to Western Europe. Sediments from this period are not represented within the Cleveland Basin, but the transgression which followed in Early Cretaceous would once again re-establish deposition of marine mudstones. These fossiliferous mudstones of the Speeton Clay Formation would span almost the entire Lower Cretaceous and form laterally extensive, uniform sequence over the Cleveland Basin.

Transgression continued through the Early Cretaceous, and reached a maximum for the Mesozoic by the end of the Early Cretaceous (Figure 2.6). The sea deepened and the supply of clastic sediments decreased. These clear-water marine conditions were widespread and the subsequent chalk seas stretched across almost the entire region of Western Europe. These chalks would reach a maximum thickness of over 500 meters and would continue through to the Cretaceous Period, and into the Early Tertiary (Danian).

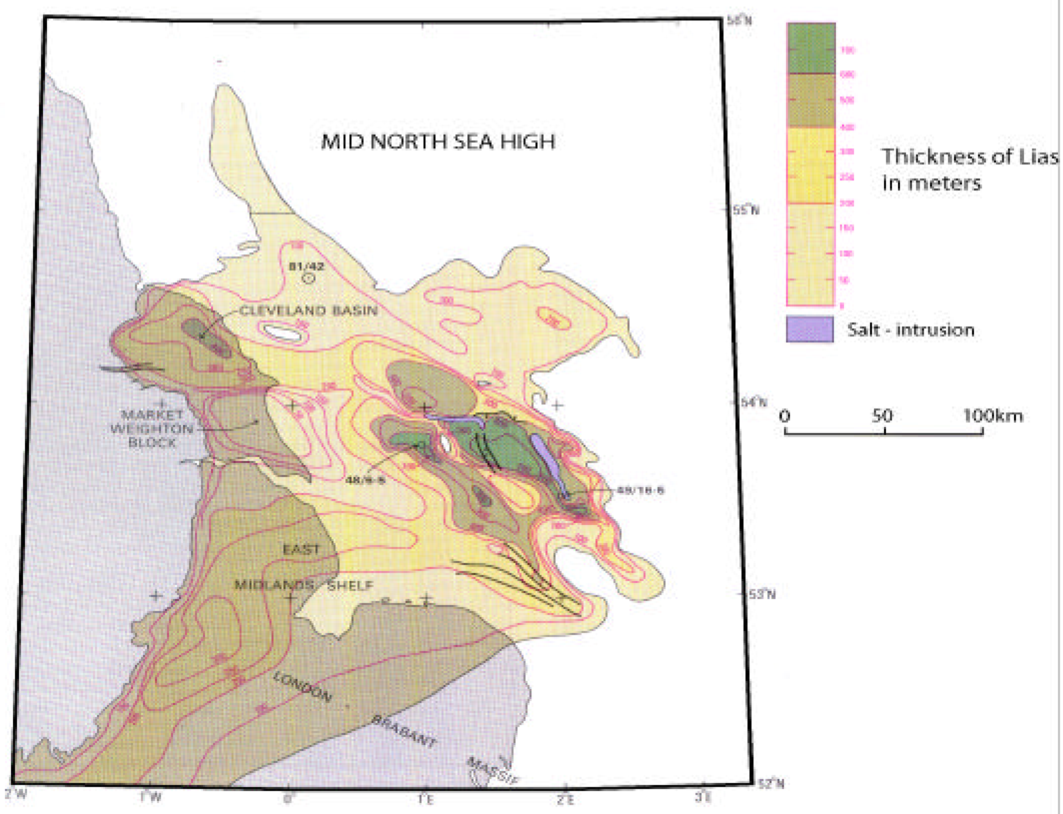


Figure 2.5. Isopach map showing thickness of Lias sediments (Modified from Cameron et. al. 1992).

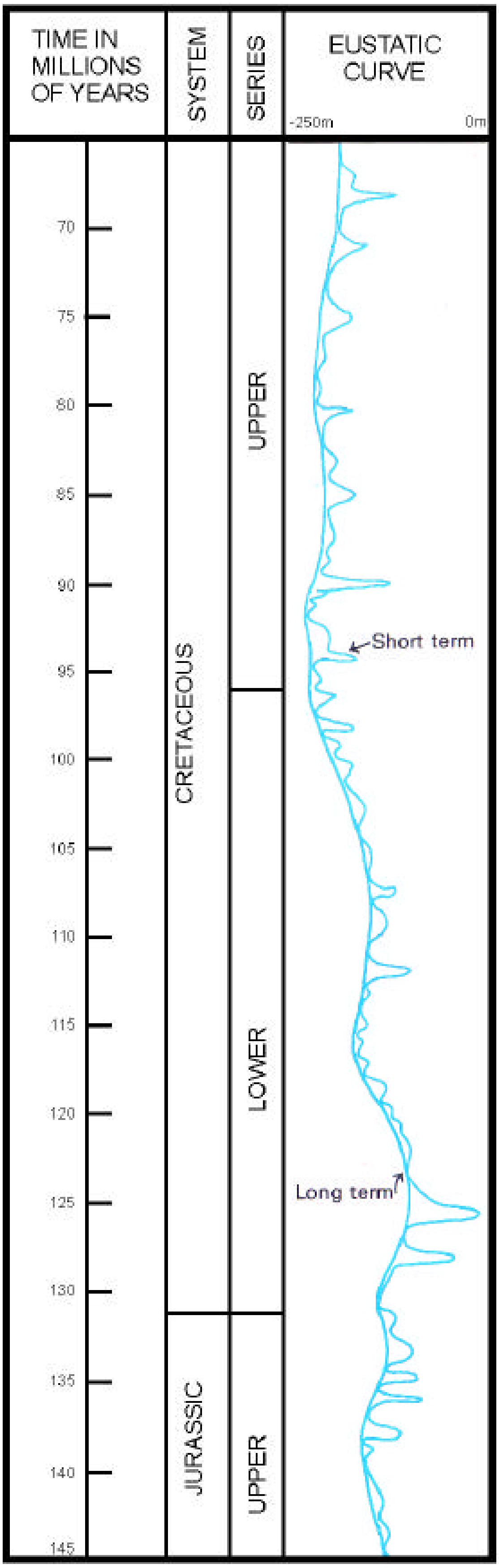


Figure 2.6. Sea Level chart from the North Sea showing eustatic sea-level curve from Late Jurassic through Cretaceous; Mesozoic maximum occurred in early-Lower Cretaceous, approximately 125 Mya (Cameron et. al. 1992) (Local tectonics probably influenced the short term curve and is therefore not purely eustatic).

2.4 Lithology - Middle Jurassic – Ravenscar Group

The Middle Jurassic period in Yorkshire was represented by a period of predominantly non-marine deposition. This sequence was previously referred to as the 'Estuarine Series' (Fox-Strangways 1892), and later the 'Deltaic Series' by Hemingway (1949). The Ravenscar Group is the name given to this sequence (Hemingway 1974), and the type locality was located at Ravenscar along the Yorkshire coast between Scarborough and Whitby (Figure 2.7). A comparison of the previous and the current classification systems for Middle Jurassic rocks can be observed in Figure 2.8. A comprehensive litho-stratigraphical log of the Ravenscar Group can be seen in Figure 2.9.

The Ravenscar Group reaches a maximum thickness of approximately 250 meters, and although it is predominantly non-marine, it does contain some periods of marine interruption. A total of three marine intervals occurred, with two of them being widespread (Figure 2.10). These two prominent marine intercalations divide the Ravenscar group into three non-marine formations; The Saltwick Formation, the Cloughton Formation, and the Scalby Formation. The Eller Beck Formation and the Scarborough Formation are the two widespread marine sedimentary units separating the above mentioned non-marine sediments. The third marine transgressive sequence was not as laterally extensive, and was therefore set into the Cloughton Formation as the Lebbertson Member (Hemingway 1974). This marine member of the Cloughton Formation locally separates the two non-marine members, the Sycarham and Gristhorpe.

As noted in the previous section, the beginning of non-marine sedimentation in the Cleveland Basin coincided with a period of uplift which occurred at the end of Early Jurassic. This period of uplift was coincident with gentle folding, and was the overall product of volcanic activity within the central North Sea. Uplift of the Mid-North Sea High provided abundant sediments which were distributed across the Cleveland Basin by southward flowing rivers. This period of fluvio-deltaic sedimentation continued for approximately 15 Ma to the end of the Bathonian. By the beginning of the Callovian, the sea transgressed and marine conditions were re-established over the Cleveland Basin.

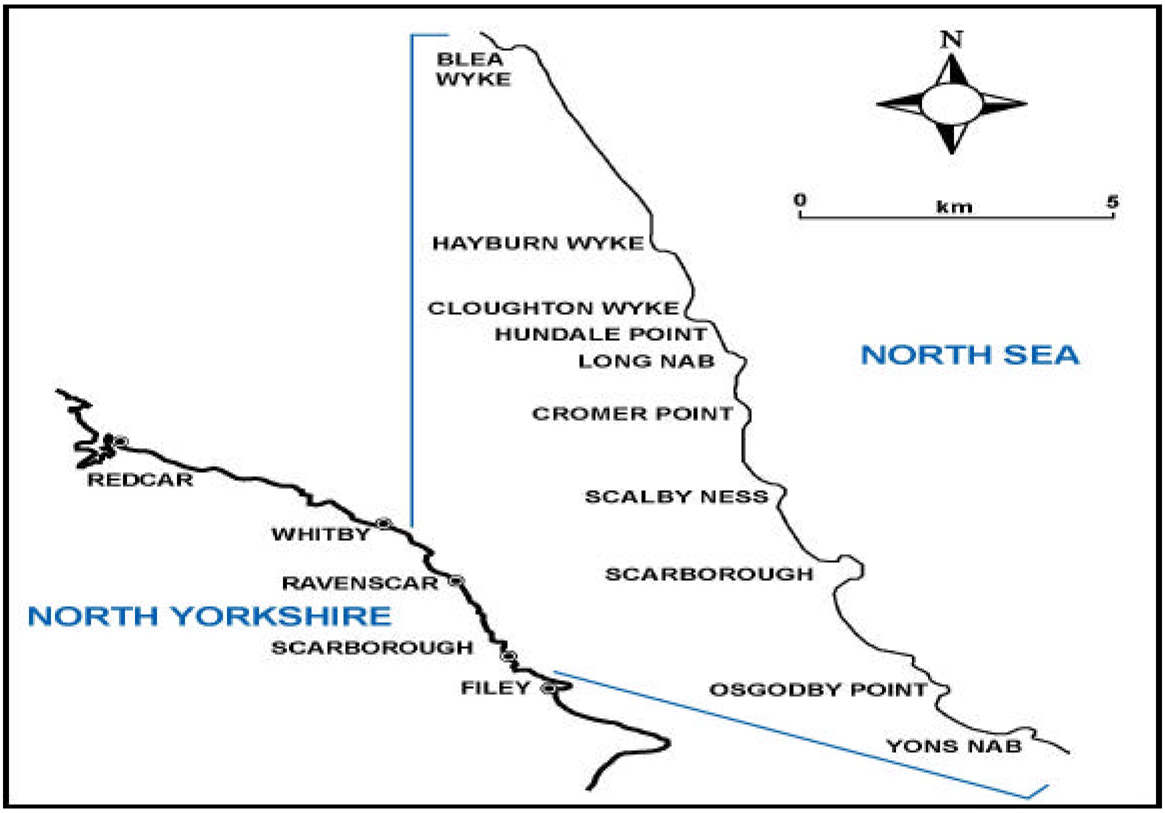


Figure 2.7. Map showing the location of Ravenscar and other investigated localities.

Fox-Strangways, 1892			Hemingway, 1949		Hemingway & Knox, 1973	
Upper Estuarine Series			Upper Deltaic Series		Scalby Formation	
Scarborough or Grey Limestone Series			Grey Limestone Series		Scarborough Formation	
Middle Estuarine Series			Middle Deltaic Series	Gristhorpe Sub-Series	Cloughton Formation	Gristhorpe Member
Millepore Series				Millepore Sub-Series		Lebbertson Member
Lower Estuarine Series				Sycarham Sub-Series		Sycarham Member
	Eller Beck Bed	Hydraulic Limestone	Eller Beck Bed	Hydraulic Limestone		Blowgill Member
					Eller Beck Formation	
			Lower Deltaic Series		Saltwick Formation	
Dogger			Dogger		Dogger Formation	

Figure 2.8. Classification systems for Middle Jurassic sediments of Yorkshire (Kent et. al. 1980).

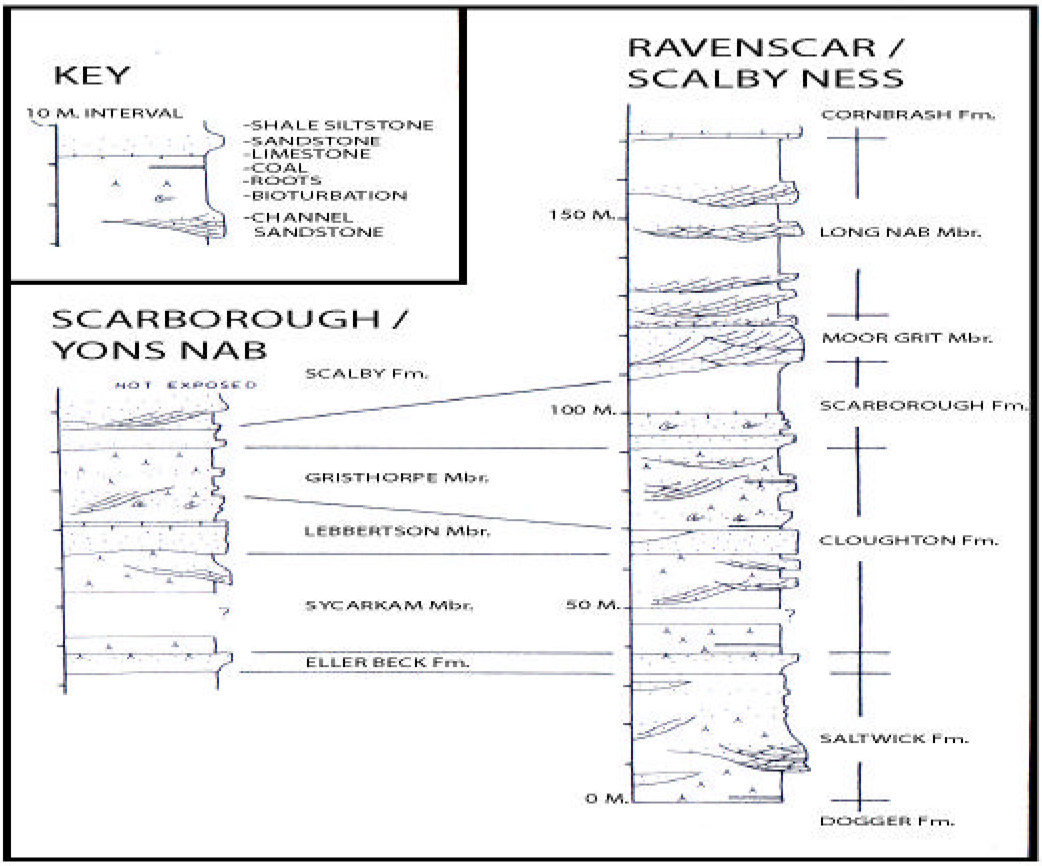


Figure 2.9. General litho-stratigraphic log of the Ravenscar Group, Yorkshire (Modified from Livera&Leeder, 1981).

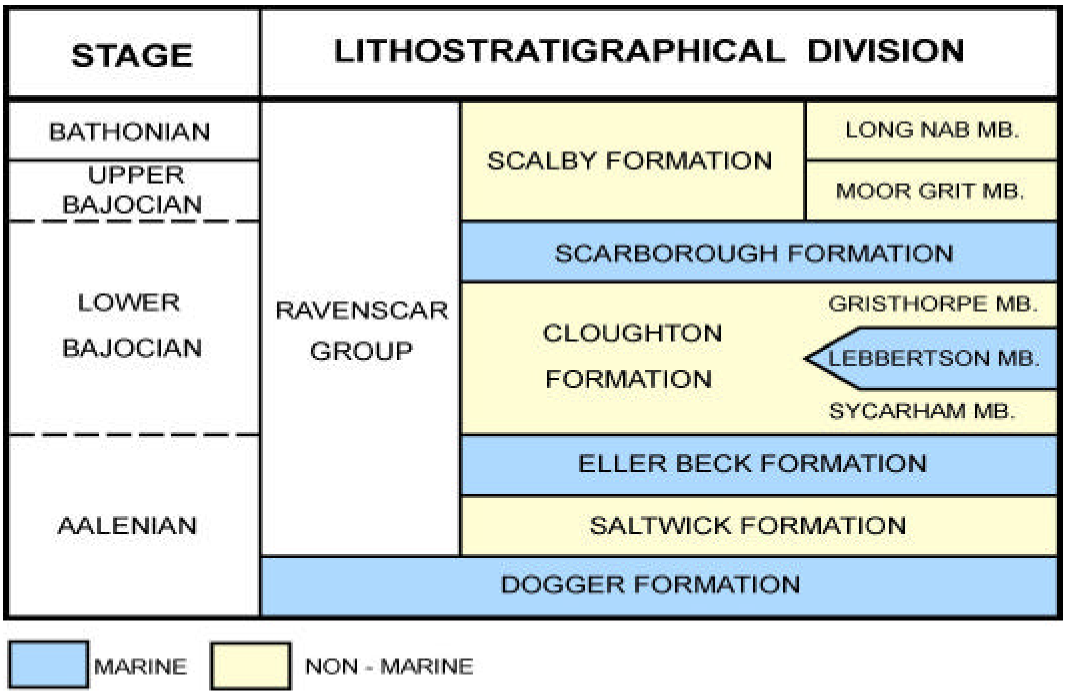


Figure 2.10. Lithostratigraphic divisions of the Ravenscar Group, Yorkshire.

2.4.1 Saltwick Formation

The first of the non-marine sequences of the Ravenscar Group are the fluvio-deltaic sandstones of the Saltwick Formation. It is classically referred to as the "Lower Estuarine/Deltaic Series". Its current name is derived from its type-section located near Saltwick Bay, Whitby. It reaches a maximum thickness of approximately 55 meters and is comprised of a series of upward fining sequences of argillaceous sandstones to silts and clays and finally carbonaceous clays or low-grade coals (Hemingway 1974). This lowest non-marine unit of the Jurassic forms an erosive surface, where the lowermost of the Saltwick formation itself, and in some places, the underlying Dogger Formation have been removed by the subsequent progradation of fluvial deposits of the later Saltwick Formation (Livera & Leeder 1981). At the base of the Saltwick Formation, large composite channel sandstones are prevalent, whereas upwards through the sequence, it becomes increasingly dominated by overbank deposits with less common channel sand deposits, less evidence for desiccation, and a greater abundance of plant material (Hemingway 1974). These vertical variations within the Saltwick Formation have been interpreted by Livera & Leeder (1980, p.241), as indicating "a transition from a well drained floodplain complex with major bedload channels to a saturated marsh drained by smaller mixed load channels suggestive of gradual abandonment of a delta lobe with time."

In the cliff section between Cloughton Wyke and Hayburn Wyke (Figure 2.7), the Saltwick Formation is consistent with the above description. Exposed on this section of cliff was the uppermost part of the formation, and it was dominated by overbank facies including laterally extensive crevasse splay deposits, with only occasional channel deposits. Thick root marks which are especially typical near the base of the Saltwick Formation were nearly non-existent in the upper section at this locality.

Along the Whitby Fault, in the town of Whitby, there are substantial lateral facies variations within the Saltwick Formation. On the western side of the Whitby Fault, there is a high concentration of channel deposits forming a stacked channel complex, whereas the equivalent interval on the eastern side shows no indications of channel deposits what so ever (Figure 2.11). This is also evident on the east side of the Peak Fault, suggesting that this localized variation could be attributed to contemporaneous faulting (Alexander 1986). On the eastern side of the Whitby Fault, the Saltwick Formation is composed primarily of sub-parallel overbank facies, and the first evidence of channel deposits does not occur until the next non-marine unit, the Sycarham Member (Figure 2.12). This indicates that the Whitby Fault was active during this period, and was the controlling factor on the localized distribution of channel sandstones. This would continue until the time of Sycarham deposition (Lower Bajocian), where channels were able to migrate over the fault, indicating the termination of this period of movement along the Whitby Fault.

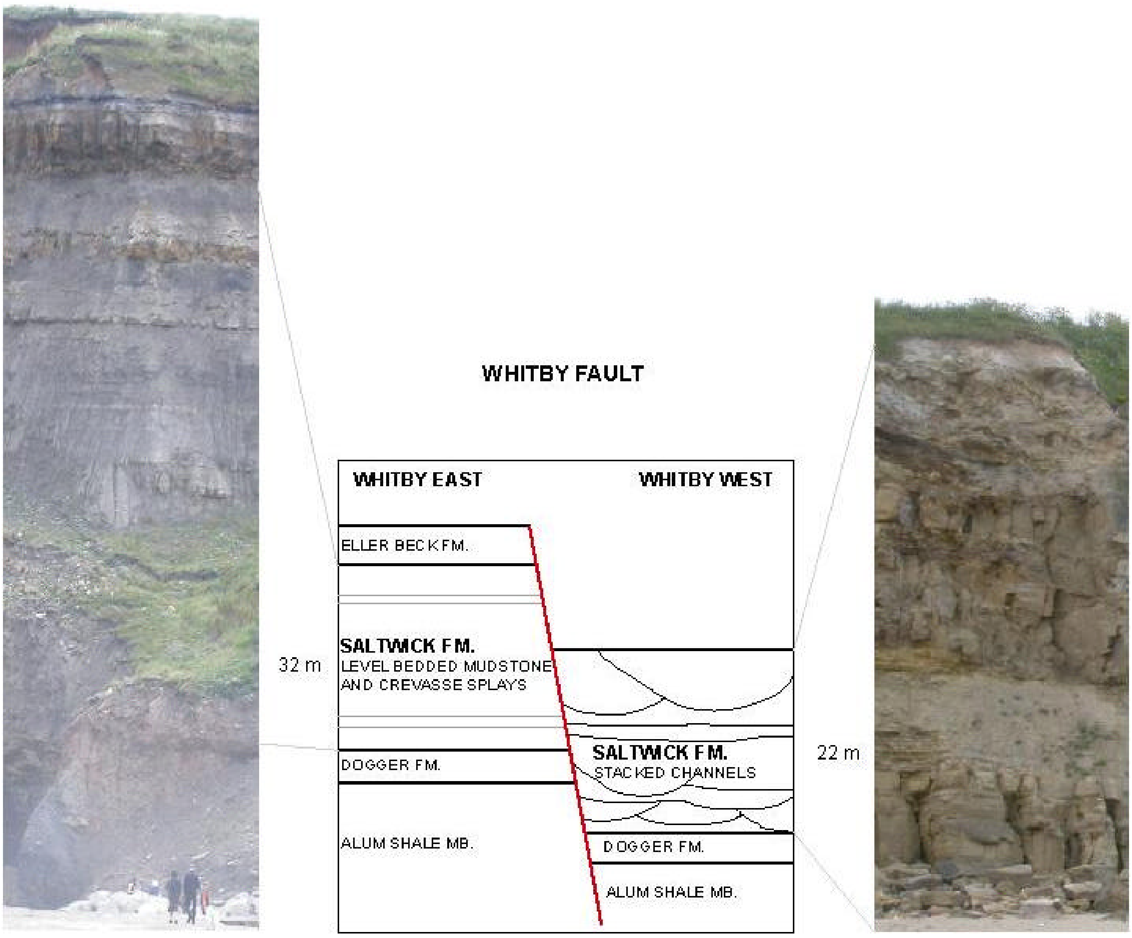


Figure 2.11. Whitby fault showing the difference in deposition within the Saltwick formation; note that stacked-channels only occur on the west side of the fault whereas the east side is dominated by flat-lying mudstones and crevasse splay deposits. Total offset approximately 12 meters

2.4.2 Eller Beck Formation

The subsequent flooding of marine waters over the delta-top of the Saltwick formation led to the deposition of a thin (4 – 8 meters), but widespread marine sequence across the Cleveland Basin. The type section of the Eller Beck Formation (Knox 1973) is comprised of thin, tough ironstone at the base, followed by a thicker unit of shale or limestone and passing up into a fine to medium grained, cross-bedded sandstone. It consist of a non-erosive based, coarsening-upward sequence which displays a variety of sedimentary structures such as; flat lamination, low angle cross-bedding, and well developed flat crested ripple sets (Livera & Leeder 1980). Bioturbation is commonly observed, especially within the middle parts of the sandstone indicating relative moderate wave energy. These conditions of a stable marine, elongated platform may have been the result of a bay type setting produced by the emergent Mid-North Sea High which moderated the wave energy within the Cleveland Basin (Bjørlykke, personal communication during G300 Field Excursion, 2003). The tops of the sandstones show an abundance of root colonization, commonly destroying sedimentary structures. This represents the gradational transition into the next non-marine, fluvio-deltaic formation (Cloughton Wyke Formation, Sycarham Member).

In the Cloughton Wyke area, the base of the Eller Beck Formation is marked by approximately 10 cm thick, laterally extensive ironstone (siderite, Figure 2.13). This layer contains abundant bivalves, gastropods, and trace fossils. Overlying the ironstone base, there are interbedded sands and silts with occasional discontinuous siderite layers. The top 1.8 meters is composed of an upward coarsening, fine to medium grained sandstone, with common low-angle cross-stratification, and rootlet structures. The very top displays a good example of flat crested ripple lamination (Figure 2.14).

The widespread and uniform lateral extent of the Eller Beck Formation across the Cleveland Basin indicates a low relief, probably marshy depositional surface. It was deposited under the conditions of a prograding shoreline on a delta front, influenced by wave and tidal currents. This coarsening up unit demonstrates a transition from the deposition of offshore mud and silt (<FWWB), to shoreface cross-bedded silts and sands (>FWWB), and finally to laminated foreshore sands (Figure 2.15).

Figure 2.12. Picture showing channel deposits within the Saltwick Fm. Whitby East.

Figure 2.13. Picture showing siderite nodules within the Eller Beck Formation.

Figure 2.14. Picture showing abundant and well developed wave ripples on the top of the below figure, Eller Beck Formation.

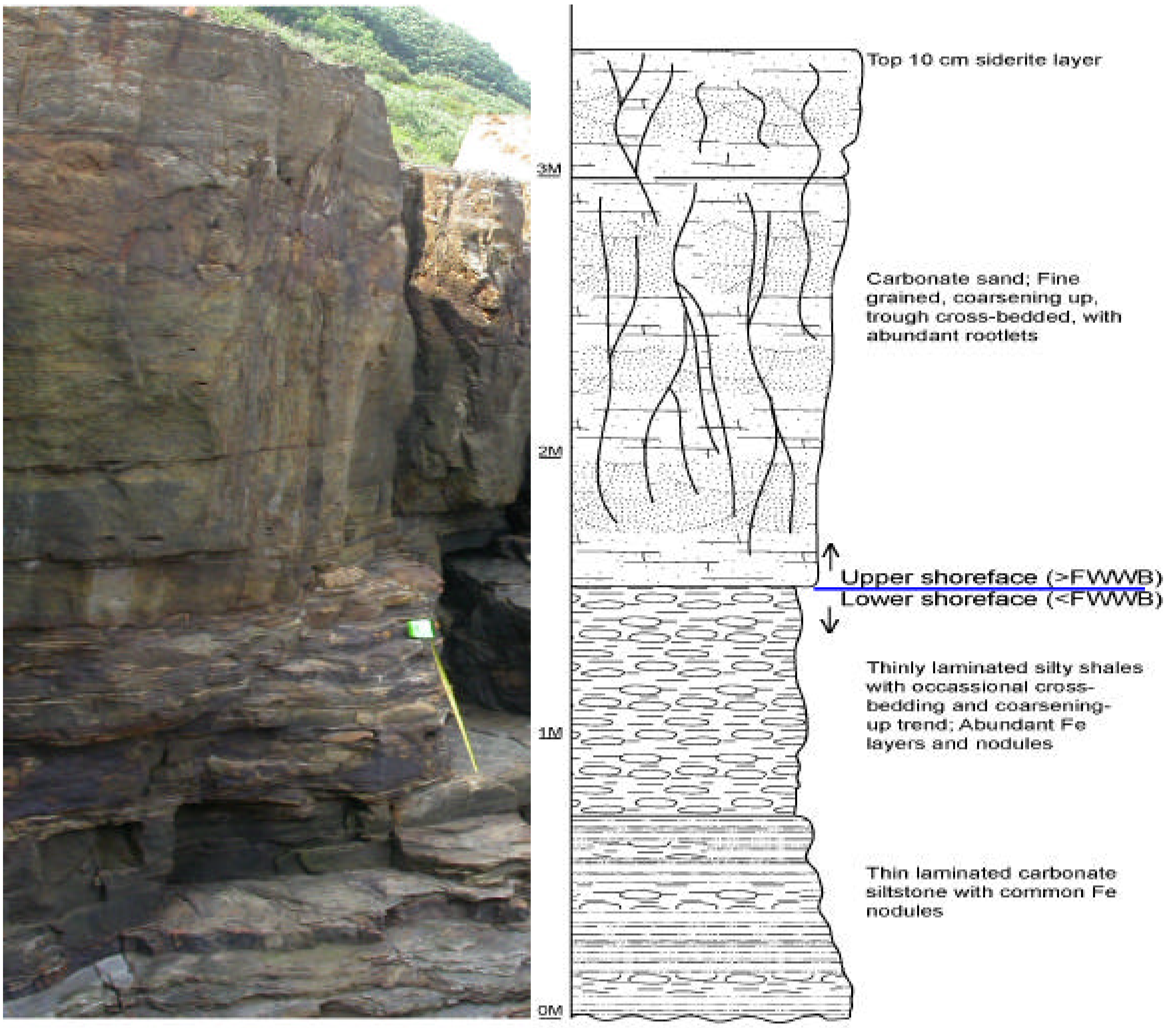


Figure 2.15. Picture and lithologic description of an Eller Beck outcrop, North of Cloughton Wyke.

2.4.3 Cloughton Formation

The Cloughton Formation is classically referred to as the "Middle Estuarine/Deltaic Series". It is similar to the Saltwick Formation with respect to the fact that it is composed primarily of overbank mudstone facies which is commonly cut by channel sandstones. It does not display the vertical trends like those of the Saltwick Formation, and fluvio-deltaic deposition is interrupted by a transgression and marine intercalation. This marine interval, the Lebbertson Member, divides the formation into two non-marine units; the Sycarham and Gristhorpe Members.

The Sycarham Member:

The Sycarham Member represents the next non-marine unit overlying the Eller Beck Formation, and is the lowest member of the Cloughton Formation. It reaches a maximum thickness of 50 meters, and is dominantly fresh water fluvio-deltaic deposits. This typically consists of isolated sand filled channels set in a matrix of interbedded shales and composite sand bodies, i.e: crevasse splays. The channel bodies show evidence of lateral accretion which marks the beginning of a meandering distributary system on the floodplain (Livera & Leeder 1980). The Sycarham Member reaches a maximum thickness in the north and thins southward probably due to erosion by the overlying Lebbertson Member (Livera & Leeder 1980). In some of the lower sandstone units, there is evidence of bioturbation (Diplocraterion), and together with palynofacies studies by Hancock and Fisher (1981 and 1985), this confirms that although this formation is considered non-marine, it was not entirely free from periods of marine influence. With consideration of the above, the relative abundance of sand, and channel morphology, this section is interpreted as a tidally influenced lower delta plain.

The Lebbertson Member:

The Lebbertson Member occurs in the middle of the Cloughton Formation, and is of marine origin. It separates the Cloughton Formation into two non-marine units (Sycarham and Gristhorpe Members) and is itself further sub-divided into two beds; a lower, calcareous Millepore Bed and an upper, non-calcareous Yons Nab Beds (Hemingway & Knox 1973). The Lebbertson Member, unlike the other marine incursion of the Middle Jurassic (Eller

Beck and Scarborough Formations), did not occur throughout the entire Cleveland Basin. Evidence indicates that it incurred from the south, thins northward and eventually dies out, representing only a partial transgression. As seen in Figure 2.9, it reaches a maximum thickness of approximately 15 meters in the south at Yons Nab, and thins drastically northwards to approximately 5 meters at Ravenscar.

The Millepore Bed:

The Millepore bed represents the lower, transgressive part of the Lebbertson Member. It is predominantly carbonate and lies erosively upon the reworked sediments of the underlying fluvio-deltaic Sycarham Formation. It is comprised primarily of subarkosic sandstone and oolites and commonly exhibits strong cross-bedding. Consistent with the rest of the Lebbertson, the Millepore Bed thins northward and shows major lateral variation in Lithology and sedimentary structures.

In the Cloughton Wyke area, the Millepore Bed is much thinner and shows a moderate decrease in carbonate content compared to outcrops further south (Yons Nab). It is represented by a carbonate mudstone base, overlaid by a coarsening up series of sandy-fossiliferous limestone, topped by siderite cemented hardground. Bioturbation is abundant, but there is still good evidence of sedimentary structures, such as small scale cross-stratification, and low angle/parallel lamination. This evidence suggests that deposition occurred above the fair weather wave base (FWWB), or under conditions of intermittent currents. The Millepore Member also shows a significant northward-decrease in oolite and shell debris content, and an increase in calcareous sand and iron-carbonate which suggests that deposition occurred in a more near shore environment, consistent with the northward thinning trend. The upper tier is extremely hard due to secondary siderite cementation. Evidence of karst-dissolution is exhibited, where the underlying calcite cemented strata has been eroded and later filled in with siderite-rich sediments and breccia fragments of carbonate mudstone (Figure 2.16). This indicates that the calcareous deposits have been aerially exposed and in contact with meteoric-water. This represents the top of the Millepore bed and the Maximum Flooding Surface of the Lebbertson Member. Succeeding this is the regressive Yons Nab Bed which is the transition into the next non-marine unit, the Gristhorpe Member.

Figure 2.16. Picture of breccia fragments on a exposed karst surface of the Millepore Bed.

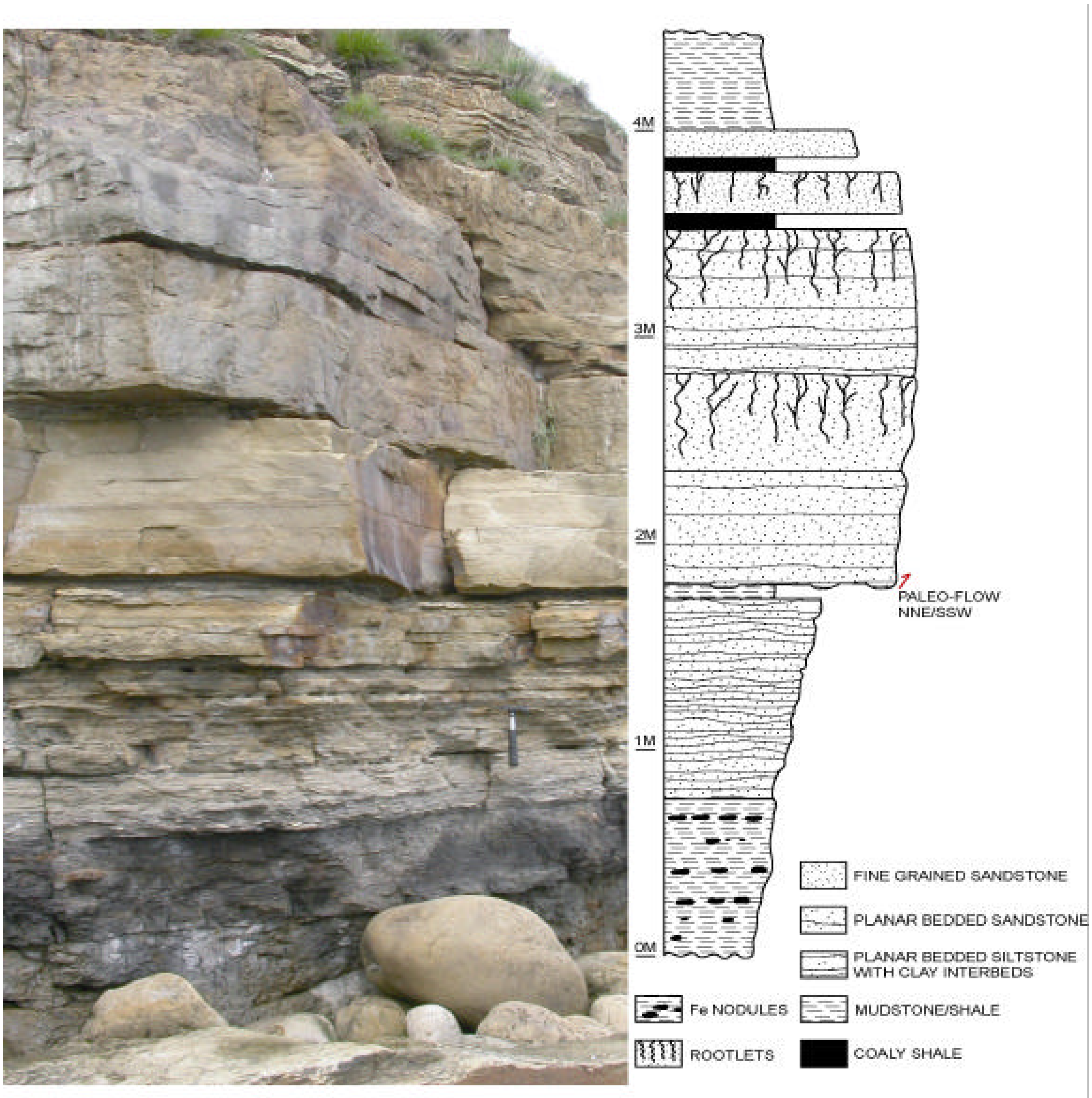


Figure 2.17. Picture and lithologic description of the Cloughton fm. outcrop, at Cloughton Wyke.

The Yons Nab Beds:

The Yons Nab Beds represents the regressive phase of the Lebbertson marine incursion, and is comprised completely of non-carbonate sediments. It displays a northward thinning trend consistent with the overall transgressive pattern of the Lebbertson Member, and is similar to the Millepore Bed, as it demonstrates marked lateral facies variation [It is important to note that the placement of these beds is a source for debate. It is suggested by Knox (Rawson & Wright 1992), who originally divided the Lebbertson Member such, that after further review, the Yons Nab bed, which is scarcely marine in some sections, should be considered as the basal part of the above lying non-marine Gristhorpe Member. Yet the undeniable marine section at the Yons Nab locality has led many researchers to continue with the original classification scheme]. At Yons Nab, this sequence is represented by a fully marine, coarsening-upward unit. Intense bioturbation is common, and only remnants of primary sedimentary structures remain. These delta front sediments are transitional, and commonly incised by the upper delta plain channel sandstones of the Gristhorpe Member.

The Gristhorpe Member:

The Gristhorpe Member represents the upper most non-marine unit of the Cloughton Formation. It reaches a maximum thickness of approximately 30 meters, and is comprised predominantly of interdistributary facies with occasional channel sand deposits. Included in these interdistributary deposits are common, laterally extensive sheet sands. Coal facies are common, and the Gristhorpe Member was the primary source for the abundant number of coal-pits found on the Moors. It is similar to the Saltwick Formation with respect to the changing upward nature where channel deposits become fewer and less substantial, and overbank facies increase.

In the Cloughton Wyke area, the lowermost section of the Gristhorpe Member consist of dark shales and coals topped by a minor coarsening-upwards sequence of siltstones and fine sandstones which are highly bioturbated (Figure 2.17). Above this occurs a series of sheet and deposits with shale interbeds. Bottom structures within these sheet sands indicate a flow-direction from the NNE to SSW (Figure 2.18), and are interpreted as crevasse splays sands which spread south-westwards across the Cloughton Wyke area as a result of repeated levee breaches from a large distributary channel to the northeast (Rawson &

Wright 1992). Abundant root structures are prominent within these sheet sands and indicate a period of plant colonization in between the individual crevasse splay events (Figure 2.19). Occasional channels incise into these lower interdistributary sediments of the Gristhorpe Member, some of which display evidence of lateral accretion i.e.: epsilon cross-bedding (Figure 2.20) in addition to large scale trough cross-bedding. These channel deposits decrease upwards through the sequence, and it becomes increasingly dominated by a mix of thin siltstones, sandstones and shales.

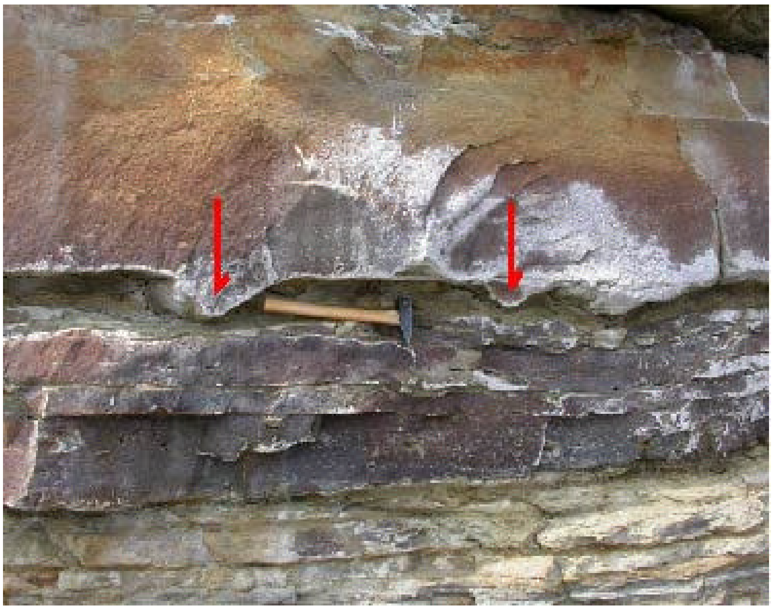


Figure 2.18. Picture showing the well developed gutter cast within a crevasse splay sand of the Gristhorpe Member. Indicating a palaeo-flow direction of NNE/SSW.

Figure 2.19. Picture of rootlets within the Gristhorpe Member, Cloughton Wyke.

Figure 2.20. Epsilon cross-beds within the Gristhorpe Member at Cloughton Wyke. Palaeo-flow NNE/SSW.

2.4.4 Scarborough Formation

The Scarborough Formation is classically referred as the "Grey Limestone Series" and represents the upper most marine unit of the Ravenscar Group. It is the thickest and best developed marine unit within the Ravenscar Group and consists of up to 30 meters of sandstones, silty and calcareous shales, impure limestones and ironstones. The lower section of the unit is represented by a fining-upwards sequence, whereas the top is a coarsening-upwards offshore to shoreface transition, which forms a erosional contact with the above lying non-marine deposits of the Scalby Formation. Depositional environments are diverse and reflect strong bathymetric variation: They range from brackish-water, sandy embayment, to wave dominated muddy and sandy shoreface, to deeper, offshore mudstones. Similar to the Eller Beck marine incursion, the Scarborough transgression also occurred from the East (Hancock & Fisher 1981). The Scarborough Formation is highly bioturbated at various horizons, and is the only formation of the Ravenscar Group to contain abundant ammonite fauna (Parsons 1977). This abundance of marine fauna, including numerous bivalves, the large Belemnite Megateuthis, and rare ammonites (Dorsetensia, Stephanoceras, and Teloceras), makes the Scarborough Formation the most accurately dated sequence within the Ravenscar Group (Humphriesianum Zone, Lower Bajocian) (Rawson & Wright 1995).

Consistent with deepening bathymetric trends southwards, the Scarborough Formation increases in thickness northwards. It is well exposed along the Yorkshire Coast, and reaches its maximum thickness of approximately 30 meters in the cliffs at Hundale Point (Figure 2.7). At this locality, the Scarborough Formation has been divided into seven members (Gowland & Riding 1991) which are summarized in Figure 2.21.

The base of the Scarborough Formation is represented by a sequence of transitional marine sandstones of the Helwath Beck Member. This is a resistive sequence comprised of sheet-like, fine grained, cross-stratified sandstones, which forms the prominent headland at Hundale Point. It displays an abundance of trace fossils (esp. Diplocraterion and Thalassinoides), particularly near the base and top (Figure 2.22), typical of shallow brackish water embayment type setting (Rawson & Wright 1995). The upper most member of the Scarborough Formation (Bogmire Grill Member) is also represented by a transitional, coarsening-upwards sandstone sequence which is commonly truncated by the overlying fluvial deposits of the Scalby Formation (Figure 2.23).

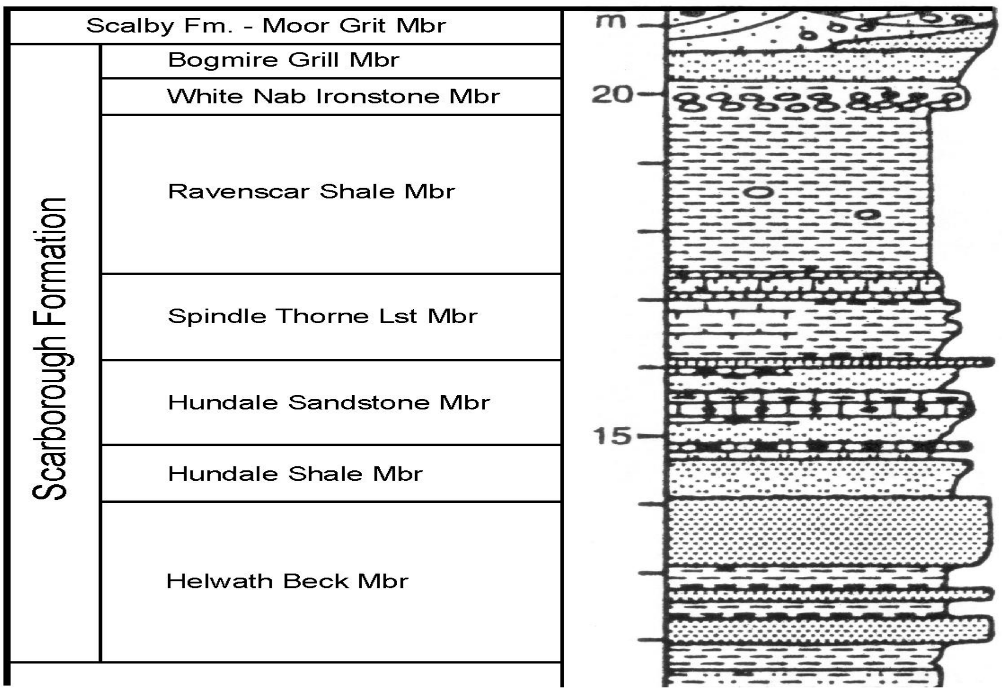


Figure 2.21. General lithostratigraphic log of the Scarborough Formation (Modified from Rawson&Wright, 1995).

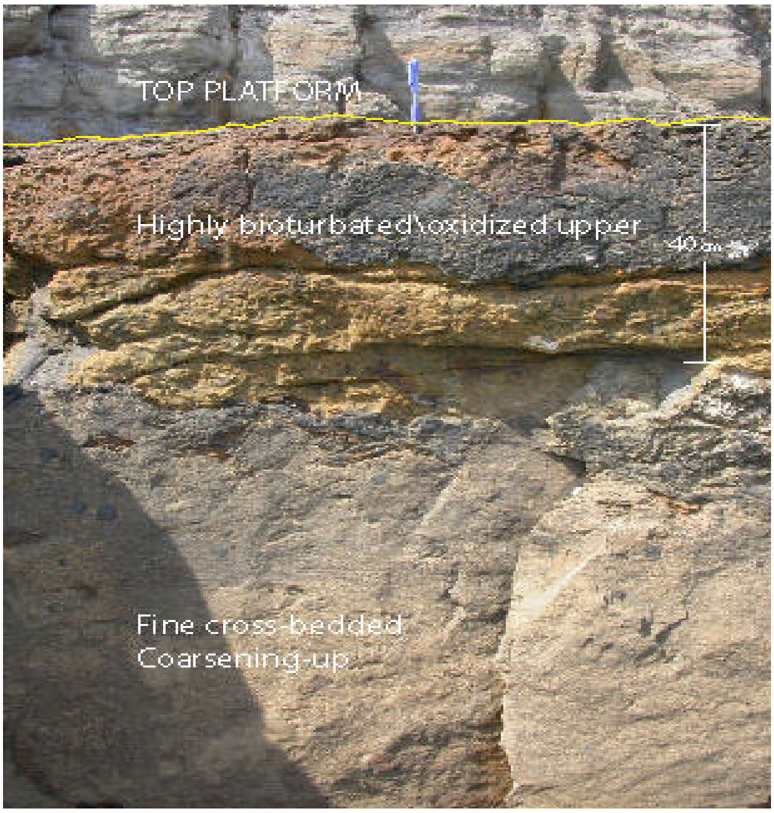


Figure 2.22. Picture of Helwath Beck Member of the Scarborough Formation showing the highly bioturbated and oxidized upper layer exposed on the beach platform at Hundale Point.

Figure 2.23. Picture showing incision of a Scalby channel sand into the underlying Scarborough Formation., Hundale Point.

2.4.5 Scalby Formation

The Scalby Formation is predominantly non-marine and represents the uppermost unit of the Ravenscar Group (Hemingway & Knox 1973). It lies erosively over the underlying Scarborough Formation, where it commonly shows substantial down-cutting and incision (Gowland & Riding 1991). The upper contact is also indicative of an unconformable contact, showing evidence of consolidation and erosion prior to the deposition of the above lying marine Cornbrash Formation (Rawson & Wright 1995). The Scarborough Formation is divided into two informal members, the Moor Grit and Long Nab, and is generally comprised of a mixed variety of channel sandstones and overbank fines. It reaches a maximum thickness of 60 meters, and paleo-direction and provenance studies indicate that alluvial channels carried sediment southward from the Mid-North Sea and Pennine Highs (Nami & Leeder 1978; Livera & Leeder 1981; Alexander 1992).

The Moor Grit Member:

The Moor Grit Member is the basal member of the Scalby Formation, and is represented by predominantly medium to coarse grained, ortho-quartzite, which was deposited as wide, multi-storey, alluvial sandstone sheets. This unit reaches a maximum thickness of approximately 8 meters, and shows cross-stratification on a large scale (Figure 2.24). These sedimentary and lithologic tendencies are characteristic for low-sinuosity, braided river with high discharge on a high slope alluvial plain (Nami & Leeder 1978).

Figure 2.24. Picture showing large scale cross-stratification of the Moor Grit Member. South of Hundale Point.

Although the deposits of the Moor Grit Member are predominantly non-marine, large scale channel deposits, there is palynological evidence which indicates that there was at least some saline influence (Fisher & Hancock 1985). This is interpreted as periodic saline water penetration between the active fluvial channels along a low-lying coastal alluvial plain (inter-distributary bay). This only occurs within the uppermost part of the Moor Grit Member, and is representative of the establishment of a more mature alluvial plain environment which was dominant during deposition of the Long Nab Member.

The Long Nab Member:

The Long Nab Member was previously referred to as the “Level Bedded Series” within Black’s (1929) “Upper Estuarine Series” and takes the present name Long Nab from its type section located four kilometers north of Scarborough (Nami & Leeder 1978). It reaches a maximum thickness of approximately 50 meters, and is comprised predominantly of planar bedded, fine-grained sediments which are commonly cut by non-continuous channel sands and fine-grained, laterally extensive sheet sands. The Long Nab Member lies erosively upon the Moor Grit and is represented at its base by a broad meander belt complex (“exhumed meander-belt” Nami 1976) which is well exposed on the wave cut platform between Scalby Ness and Hundale Point. This boundary is noted by the transition from the lower lying, large scale cross-bedded, coarse-grained channel sandstones to increasingly muddy sandstones showing well developed lateral accretion features, i.e. epsilon cross-beds. Above the meander belt sand, the unit becomes increasingly fine-grained and is composed primarily of mudstones with occasional crevasse splay sands. These overbank facies deposits are occasionally incised by coarser channel deposits (Figure 2.25 & 2.26).

In contrast to the Moor Grit Member, the channels of the Long Nab seem to be of high sinuosity with relative low discharge. It is influenced much more by finer grained, floodplain type deposits with only occasional channel sands. Palynological studies have shown significant marine influence (Fisher & Hancock 1985), which has created much debate on the subject of depositional environment [coastal plain (Nami & Leeder) versus delta (Hancock and Fisher)]. Despite the ongoing debate, the Scalby Formation is a predominantly non-marine unit with an increasing marine influence upwards.

Deposition of the Scalby Formation spanned much of the Bajocian and Bathonian (Riding & Wright 1989). It is estimated by Leeder and Nami (1979), that there is approximately ten million years of sediment missing from this period corresponding to the Scalby Formation. This was originally interpreted as a major hiatus at the base and/or top of the Scalby Formation (Nami & Leeder 1979). After further palynological studies (Fisher & Hancock 1985), it was proposed and generally accepted that the Scalby Formation probably represents a long period of much interrupted sedimentation, instead of one long hiatus proposed by Leeder and Nami.

Throughout deposition of the Long Nab Member, marine influence is evident, and this trend increases upwards, where it finally gives way to the fully marine environment of the overlying Cornbrash Formation. This transgressive event would mark the end of non-marine deposition within the Middle Jurassic, and the subsequent dominant marine settings of the Upper Jurassic.

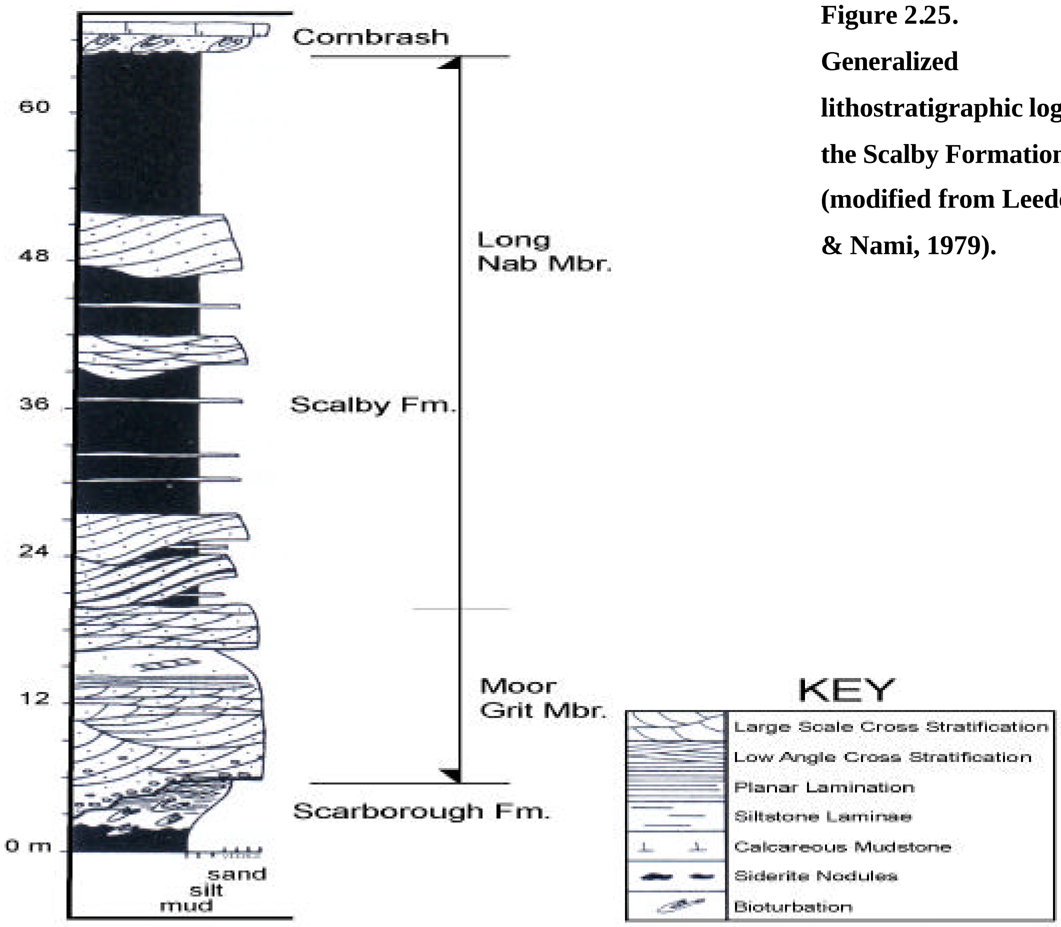


Figure 2.25. Generalized lithostratigraphic log of the Scalby Formation (modified from Leeder & Nami, 1979).

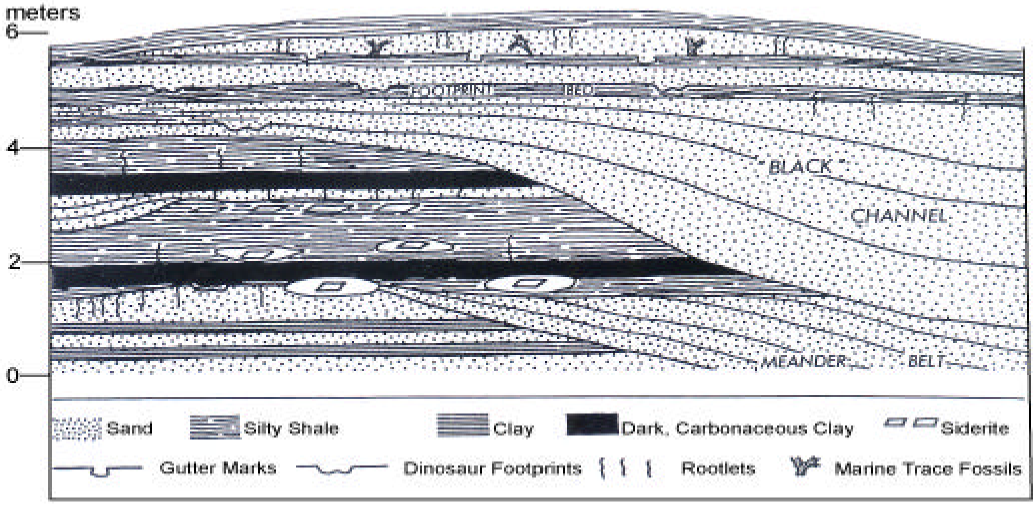


Figure 2.26. Cross-section within Burniston bay showing the incision of channel sands into the underlying formations (Nami & Leeder, 1978, p. 435)

Chapter 3 Sandstone Facies of the Ravenscar Group

3.1 Introduction – Ravenscar Facies

The Middle Jurassic of Yorkshire is comprised almost completely of non-marine sandstone deposits. The term fluvio-deltaic has been loosely applied to the Ravenscar Group due to the varying degree of marine influence, and is a source for ongoing debate and research. It is generally agreed that the lower two units, the Saltwick and the Eller Beck Formations, are of fluvio-deltaic nature and represent a transgression and gradual abandonment of a delta lobe (Livera & Leeder 1981). The Gristhorpe Member of the Cloughton Formation shows abundant marine influence, and is interpreted as deltaic with a prograding sequence from marginal marine sands through crevasse splay sheet sands into lacustrine and interfluvial deposits (Rawson & Wright 1995). The source of most debate within the Ravenscar Group is the sandstones of the Scalby Formation. It is interpreted as a coastal plain environment by Nami and Leeder (1979) and as a deltaic environment by Hancock and Fisher (1985). It is for this reason that the term fluvio-deltaic has been applied to the Scalby Formation.

In order to compare and contrast the reservoir properties of different sandstone types, it is necessary to have a good understanding of the different depositional environments or sedimentary facies. A sedimentary facies is defined as 'any aerially restricted part of a stratigraphic unit that exhibits characteristics significantly different from those of other parts of the unit' (Reading 1996). The characteristics of these different facies determine reservoir properties and can vary greatly from one adjacent facies to another. In addition to the understanding of these individual facies, it is also necessary to understand the relationship and interplay between them (*facies association*, Collinson 1969). With some knowledge about the interplay between a group of related facies, the ability to predict reservoir characteristics increases greatly. For example, the stacking patterns of fluvial channels and their relationship to overbank deposits, controls the degree of interconnectedness and internal communication within a reservoir (Reading 1996).

This chapter will include a general description of the represented sandstone facies within the Ravenscar Group and their typical reservoir properties. This will include; shallow marine facies - upper and lower shoreface sands, typical of the Eller Beck Formation; alluvial overbank facies - crevasse splays sands, typical of the Gristhorpe and Sycarham

Members; and channel sandstone facies typical of the Saltwick and Scalby Formations. The following facies description and reservoir characteristics are based on; Reading 1996, and Bjørlykke 2001.

3.2 Shallow Marine – Near Shore and Offshore Transition Zones

The near shore zone extends from the mean fair weather wave base (FWWB) to the mean high water level (MHW) (figure 3.1). This includes the upper and lower shoreface which extends from the FWWB to the mean low water level (MLW) and the foreshore which lies between the MLW and MHW. The shoreface zone is where fair weather waves begin to touch the bottom and is the zone of maximum sediment movement. Typical sedimentation features include; symmetrical ripples passing landward into symmetrical ripples; dunes; storm deposited facies such as laminated and bioturbated facies. The offshore transition zone includes the area between the mean storm weather wave base (SWWB) and the FWWB. This zone is characterized by alterations of high (storm) and low (fair weather) conditions. Low energy periods coincide with deposition of fine-grained sediments which settle from suspension and where bottom sediments are typically bioturbated. During periods of high energy the bottom is affected by oscillatory waves, shoaling waves and storm induced currents. Periods of fair weather deposition are normally erased by periods of high energy so the depositional features within the transition zone are usually dominated by storm depositional features. Typical sedimentation features include; storm-generated sand beds of laminated, hummocky cross-stratified (HCS), and bioturbated facies; mud and silt interbeds deposited during periods of fair weather.

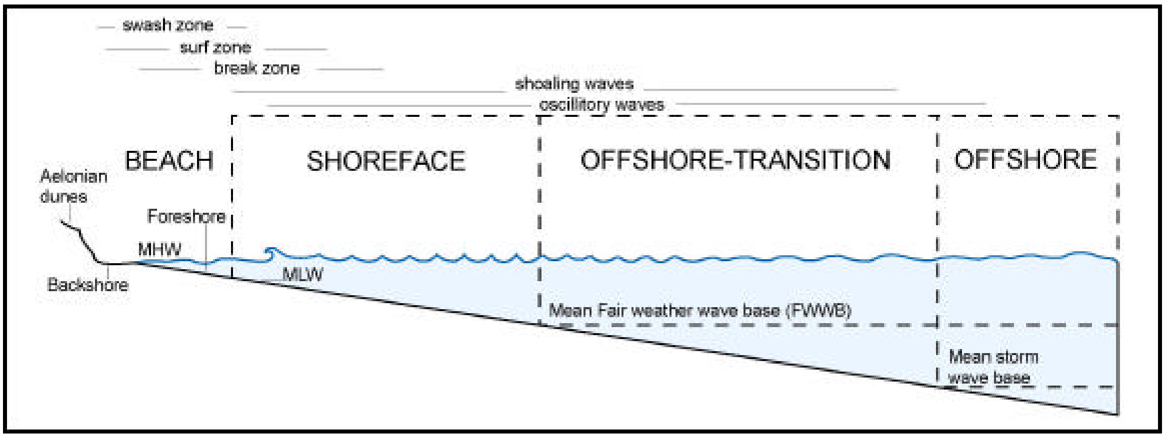


Figure 3.1. Generalized shoreline profile showing sub environments and facies (Reading 1996).

The Eller Beck Formation of the Ravenscar Group is typical of these near shore and transition zone depositional environments. As seen in the previous chapter (figure 2.15), the Eller Beck Formation represent a shallowing-up sequence where a transition from the lower shoreface - transition zone to the upper shoreface is clearly delineated.

Sandstones from shallow marine facies generally have very good reservoir qualities. Due to wave action, they tend to be well sorted, and most of the fine grained ma terial has been washed away, which leads to very good porosity and permeability. In addition, they are stratigraphically associated with potential source and seal units from underlying offshore shales and overlying shelf mudstones respectively, and they commonly subject to stratigraphic trapping (pinch-out, truncation).

3.3 Alluvial Overbank – Levees and Crevasse Splays

Overbank facies make up an important part of the alluvial plain depositional environment. They are associated with all types of channels and can be divided into either proximal or distal. The proximal overbank facies are those deposited close to active channels and are made up of crevasse splay and levee deposits. Distal overbank facies are those which are deposited some distance from active channels onto the floodplain and composed primarily of fine grained sediments (mudstones, palaeosols, and coals).

Levees are the ridges that occur along the margins of a channel. They are developed along both sides and are generally largest along the outside edge of curves (Figure 3.2). Levee deposits are predominantly composed of fine grained sands and silts which are dominated by ripple cross-lamination and small scale cross lamination. Lamination is often distorted or completely destroyed by bioturbation, and vegetation ruminants are occasional evident. Levees commonly extend laterally and become interbedded with overbank fines.

During intermittent periods of flooding, levees are compromised as floodwater overtops and incises into them. Floodwaters spread out into the adjacent lower lying floodplains and as energy and turbulence diminish, suspended sediment is deposited. Sediments deposited from this process are called crevasse splays. They are predominantly composed of fine sands and silts with the coarse fraction decreasing with distance from the channel. In some cases, crevasse splay channels incise deep into the levee resulting in an increase in grain size and possible higher energy leads to more distal deposition of this coarse fraction. Crevasse splaying tends to occur in a periodic yet repetitive fashion, and although individual splays are fining-upwards, they have an overall coarsening-upwards trend due to their coalescing nature. As distance increases from the channel, crevasse splays tend to be increasingly interbedded with floodplain fines, and vegetation is common.

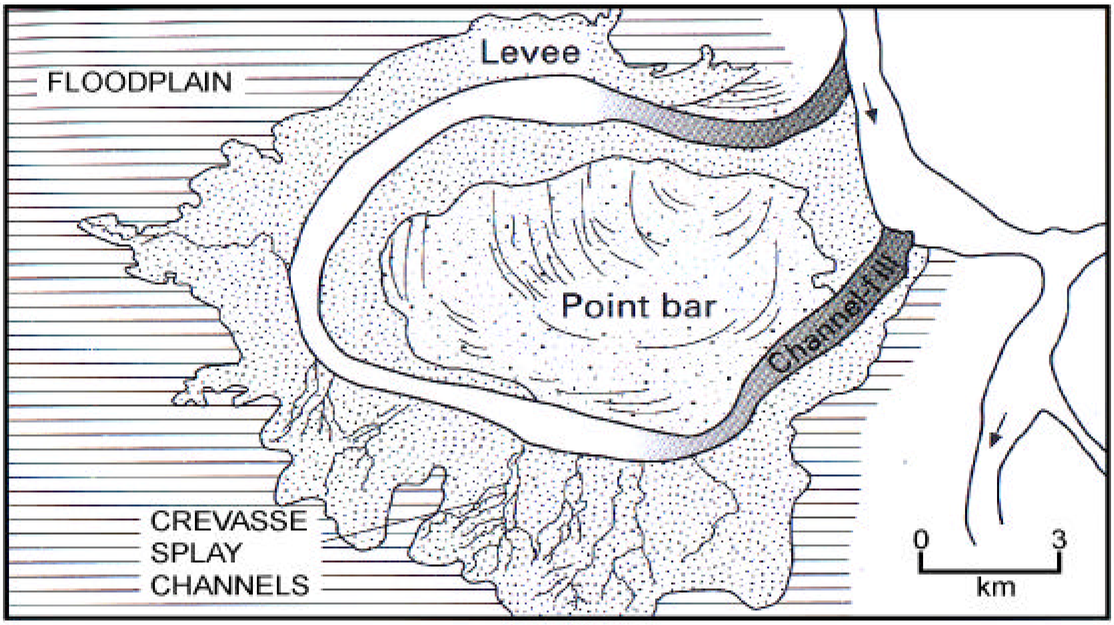


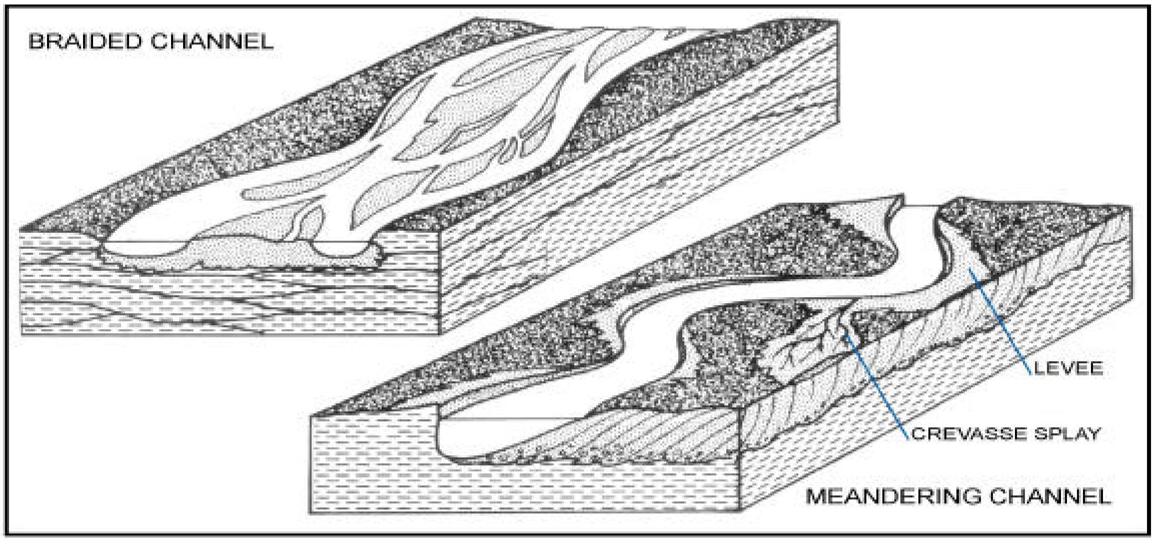
Figure 3.2. Meander river (oxbow lake) showing levee, crevasse splay channels/deposits and floodplain association (Reading 1996).

Levee and crevasse splay deposits are common within the Ravenscar Group non-marine sequences. A good example can be seen in figure 2.17, which shows a series of sand dominated crevasse splays interbedded with mudstones and coals.

Crevasse splays and levees are not considered to have good reservoir qualities due to their high fraction of fine grained sediments, but their interplay within deltaic and fluvial reservoirs can be very important. Although their porosity and permeability will be significantly lower compared to adjacent sandstones, it is possible that they can maintain adequate permeability, and improve overall reservoir communication. In some cases, a crevasse splay sand may provide a pathway connecting two otherwise unconnected channel sands. Although small, crevasse splays can have a marked affect on interconnectedness and the overall net to gross of a petroleum reservoir.

3.4 Fluvial Channel Sandstones – Meandering and Braided Rivers

The Fluvial system plays the most significant role in sand distribution. It has strong influence on the alluvial, delta and shallow marine depositional environments. Transport of sediment in a fluvial channel is dependent upon; stream gradient, profile, discharge, and the calibre and amount of sediment. These determine the type of sedimentary structures and geometry of sandstone deposits, including the overall shape and form of channels. Fluvial channels can be divided into three main types based on form; anastomosing, meandering, and braided (anastomosing channels are not present within the Ravenscar Group, and will therefore not be discussed in this section). A summary of characteristics for both meandering and braided channels can be seen in figure 3.3.



	BRAIDED CHANNEL	MEANDERING CHANNEL
Geometry	sinousity < 1.5	sinousity > 1.5
Grain Size	coarse sand and gravel	fine to medium sand with thin basal lag; common interbedded fines
Typical Log Profile	large scale cross-statification and trough cross lamination with thin ineterbeds of sand and silt; occasional upward coarsening	fining-upwards sequence
Stream Gradient	generally greater than meandering channels	low to moderate
Sediment Type	relative low clay and silt content; lower levee stabilty due to greater discharge and less cohesive material	significant clay and silt content; good levee stability due to cohesive material
Discharge	relative large variations	relative moderate variations
Vegetation	less common; reduces erosion	common; stabilize channel

Figure 3.3. Summary of typical characteristics for meandering and braided fluvial channels (Bjørlykke 2001).

Present within the Ravenscar Group is both meandering and braided channel deposits. The Scalby Formation is an excellent model displaying a major braided distributary channel within the lower Moor Grit Member and a well exposed meander belt within the overlying Long Nab Member (figure 2.5 & 2.6).

Channel sandstones generally have good reservoir properties. But this is very dependent upon primary sediment composition, fraction of fine grained material and overall geometry. Fluvial sandstones can have a high primary clay content, which can severely reduce porosity and permeability. In addition, channel sands can be long and thin or stacked in fashion where communication is limited by interbedded or associated fine grained sequences. This tends to be the case with meandering channels where discontinuity of sand bodies and a high fraction of fine grained material make them less desirable reservoir prospects. Braided channels, on the other hand, generally have better potential. They tend to have a coarser average grain size, and the possibility is greater for more continuous vertical communication.

Chapter 4 Data and Methods

4.1 Data

Comprehensive field work was completed in conjunction with the University of Oslo's annual field excursion to Yorkshire, headed by Knut Bjørlykke, and an additional two weeks completed independently immediately after. Field work was limited to coastal exposures along the 65 km stretch from Filey Brigg to Whitby. A total of 72 field samples were taken from the different representatives of the Ravenscar Group, of which 44 thin sections were prepared by the technical staff at the University of Oslo. Thin sections were impregnated with blue epoxy and polished. Below in Figure 4.1 is a summary of field samples and thin sections with their associated formation and type of analysis.

Formation Member	**Total Samples**	**Thin Sections**	**XRD**	**SEM**
Scalby				
Long Nab	12	4	1	1
Moor Grit	12	6	1	1
Scarborough	4	2	1	1
Cloughton				
Gristhorpe	22	14	2	2
Lebberston	2	2	1	0
Sycarham	4	3	2	2
Eller Beck	4	4	1	1
Saltwick	11	8	4	4
Dogger	1	1	0	0
Total	**72**	**44**	**13**	**12**

Figure 4.1. Table displaying a summary of sample types and their associated formations and type of analysis.

Samples from different depositional facies (channel sandstone, crevasse splay sandstone, and marine sandstone) were selected and prepared for x-ray diffraction (XRD) and scanning electron microscope (SEM) work.

4.2 Methods

The following techniques have been used in this study:

1.) Scanning Electron Microscope (SEM)

*Backscatter Imaging (BSI)

*Secondary Electron Imaging (SEI)

*Cathodoluminescence

2.) X-Ray Diffraction

*Bulk Analysis

*Clay Fraction Analysis

3.) Net/Gross (N/G) Estimates Based on Digital Photographs and Lithostratigraphic Logs

4.2.1 Scanning Electron Microscope (SEM)

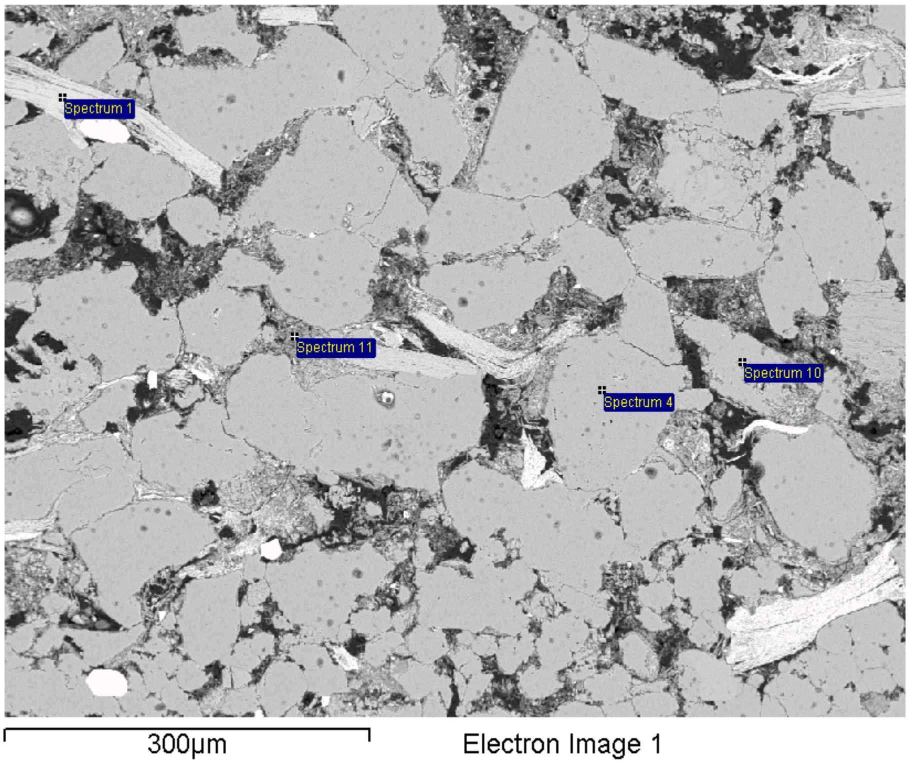
A total of 12 thin sections were selected from the different depositional facies for examination with a scanning electron microscope. Analyses were performed at the Department of Geology, University of Oslo, using a JEOL-JSM6460LV Scanning Electron Microscope attached to the INCA-Microanalyser system. Samples were analysed primarily by the use of backscatter electron image (BSE), with some use of secondary electron image (SEI). Samples were polished and coated with < 3µm thick carbon coating to eliminate the electrical charge that gathers due to an incident electron beam.

Backscatter electron imaging was used to measure the relative amounts of porosity, detrital and non-detrital grains. In backscatter imaging, a number of detectors, which lie at high angles to the sample plane, are used to examine the electrons reflected back from the sample (backscattered electrons). The term backscatter coefficient is used to measure the degree of backscatter. This is based on the different densities, i.e. atomic number, and therefore represents the mean atomic number of the element at that given spot of the specimen. The higher the atomic number, the brighter it will appear on the screen. We can therefore use these different contrast energies to represent certain mineralogical features within the sample.

Using a function of the INCA-microanalyser software program, it was possible to measure the volumetric relationship between porosity, detrital and non-derital grains based on the above mentioned backscatter coefficient and differences in contrast energy. Spectral analyses were first performed to identify mineral composition and then matched to its respective contrast energy as a means of calibration. Contrast intensities have been divided into 4 different categories based on spectral analyses and go from lightest to brightest:
1.) Porosity
2.) Non-detrital clay (kaolinite)
3.) Detrital (quartz and feldspars)
4.) Heavier minerals (Fe, Mg, Ti, i.e. muscovite)

The following figures show a breakdown of the procedure from spectral analyses calibration (Figure 4.2), to contrast intensity display (Figure 4.3), and finally a volumetric measurement of the different contrast intensities (Figure 4.4).

Yorkshire1 SW1-2-SITE5 (ZOOM X170)



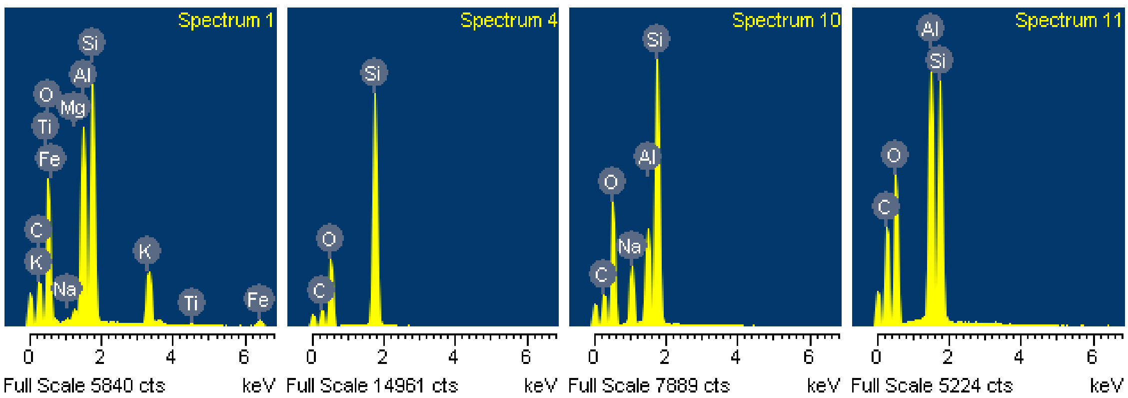


Figure 4.2. Spectral analysis showing the main minerals present: 1.) Muscovite; 4.)Quartz; 10.) Plagioclase; 11.) Kaolinite.

Yorkshire1 SW1-2-SITE5 (ZOOM X170)

Project: Yorkshire1 Owner: Chris Peltonen Site: Site of Interest 5	Sample: Sample 9 Type: Channel ID: sw1-2

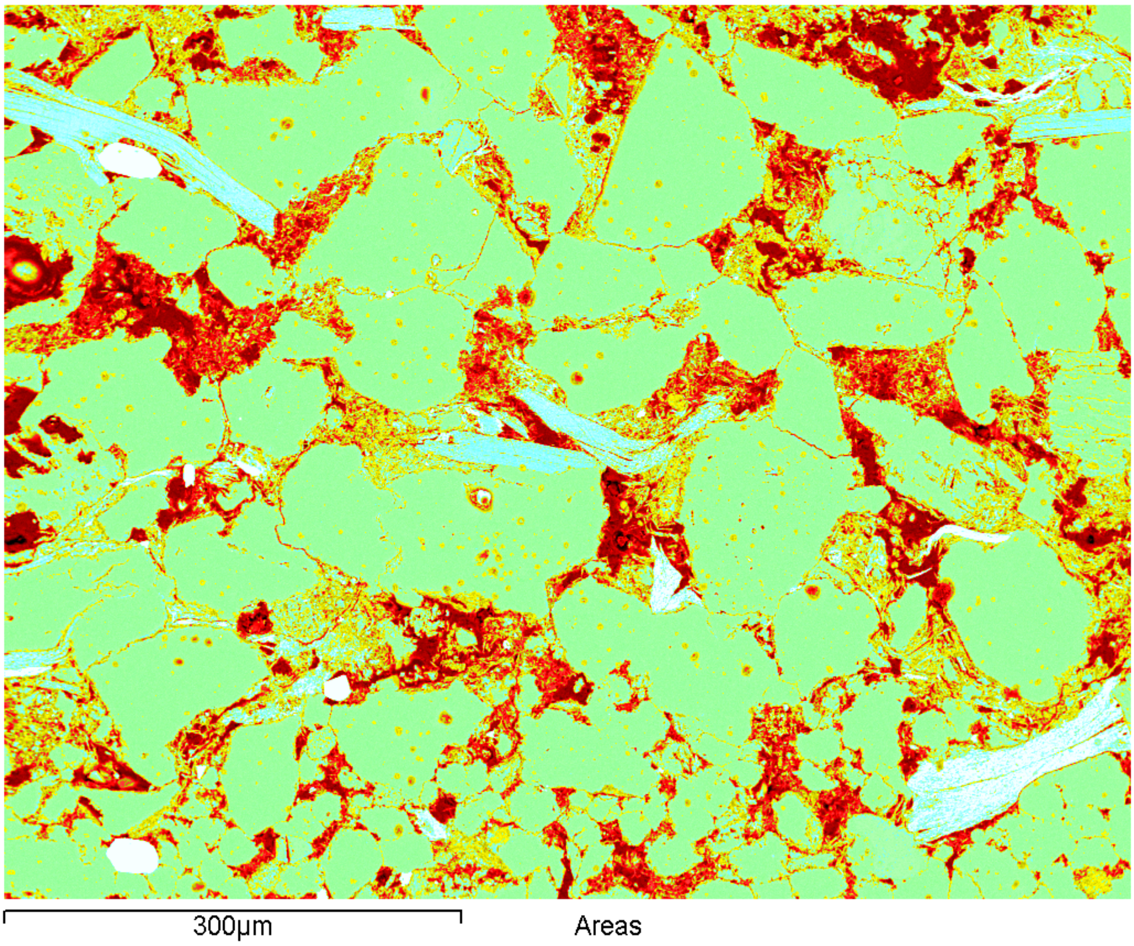
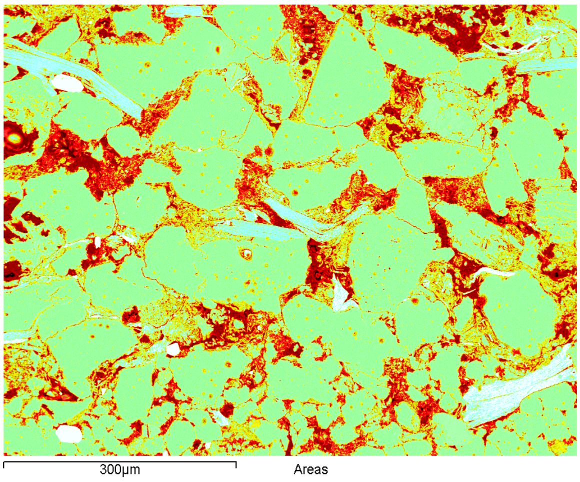
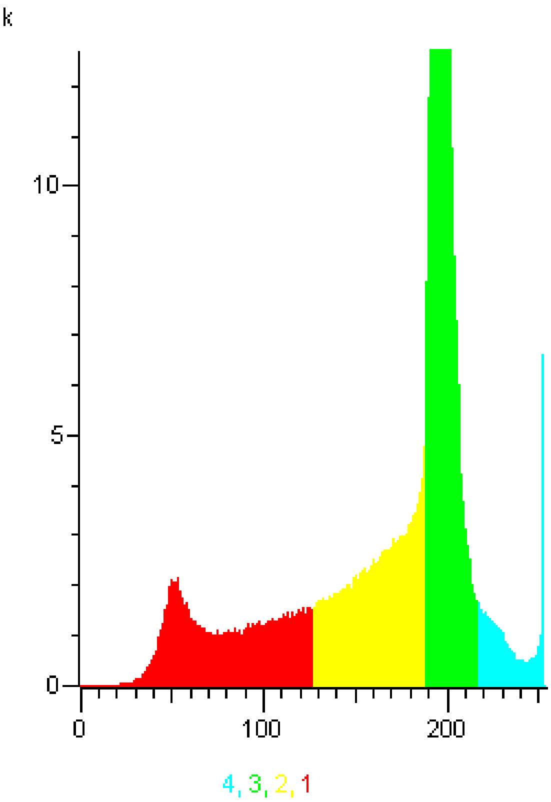


Figure 4.3.Corresponding to the previous figure, showing contrast intensities of the different elements; Porosity in red\black; Quartz grains displayed in green; Pore filling kaolinite displayed in yellow; and Muscovite and heavier elements (Ti) displayed in blue/white.

Yorkshire1 SW1-2-SITE5 (ZOOM X170)





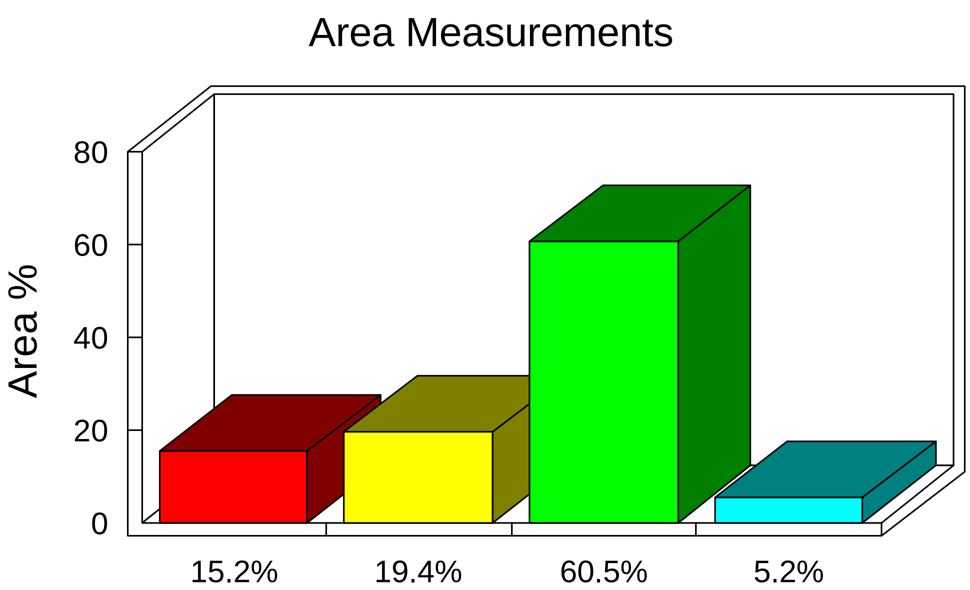


Figure 4.4. Area measurements of the different contrast intensity are used together with spectral analysis to quantify mineral composition and porosity. Red = porosity; Yellow = kaolinite; Green = detrital grains; Blue = mica/heavier minerals.

As mentioned previously, a total of twelve samples were analysed using this technique. In order to obtain more realistic measurements, a minimum of four areas were chosen randomly to represent each sample. These are noted as site1-4 respectively. Thorough spectral analysis was completed with very little variation in the type of authigenic clay (kaolinite). For this reason, the authigenic clay portion is noted as kaolinite (XRD results also show that the primary clay fraction is Kaolinite with only minor Chlorite). The distinction between potassium feldspars, quartz and plagioclase is not accurately possible through this method and was determined through XRD analyses.

[It is not the author's intention to present these measurements as exact amounts, but rather an attempt to show the overall relationship between the different minerals and the possible implications they might have. Based on concurring XRD work, this technique does produce realistic measurements which can be used to estimate the porosity, detrital and non-detrital fraction of a relatively homogeneous data set.]

In addition to the volumetric measurements, SEM was also used for general petrographic analysis. Features such as grain size, sorting, pore-size distribution and roundness were observed through SEM backscatter imaging and secondary electron imaging. Limited cathodoluminescence was used to observe authigenic quartz development, but was not within the main scope of this paper and will therefore only be briefly discussed.

All SEM data is available for review in Appendix A.

4.2.2 X-Ray Diffraction

A total of 13 samples were prepared for XRD analysis. These samples correspond to the samples analysed using SEM (exception of one extra marine sandstone CW3-LB1). All 13 samples were analysed for bulk mineral composition and five samples were analysed for total clay (<2µm). All samples were prepared and processed at the Department of Geology, University of Oslo using the Philips *X'Pert* diffractometer with Cu-Ka radiation. Generator settings of 40kV/50mA with spin-analysis set at one revolution per second. Peak intensities used for estimated mineral composition are those from the diffracted intensities (DI) listing provided by the *X'Pert – High Score* software package.

Bulk Analysis:

The whole rock mineral identification was analysed from unoriented powdered bulk rock samples. Samples were manually crushed to a consistent fine powder and mechanical packed into an XRD slide. Samples were x-rayed from 3 to 50°2? with step size of 0.06°/3 seconds. Slow scans were run from 26 to 28.5°2? with step size set at 0.01°/4 seconds to distinguish between potassium feldspars and plagioclase.

Clay Mineral Analysis:

Clay mineral analysis was completed for the <2 µm fraction of 5 samples. Samples were manually crushed consistent with the preparation of bulk samples and placed in an aqueous settling column filled to a set height with distilled water. The samples were in solution for a fixed period of time and the desired fraction was thereafter removed by siphoning the lower most aqueous level. The samples in solution were then filtered through inverted 0.22mm millipore papers and placed on XRD slides for analysis. Samples were analysed first as untreated/air-dried with slow scan, and then ethylene glycol treatment was performed, followed by heat treatment. Air-dried samples were x-rayed from 3 to 45°2? with a step speed of 0.06°/3 seconds. The glycolated samples were heated to 60°C for a minimum of 2 hours and then x-rayed from 3 to 35°2? with a step speed of 0.06°/3 seconds. Ethylene glycol x-ray patterns were used to differentiate between smectite and chlorite. Heated samples were exposed to 550 °C for 2 hours and then x-rayed from 3 to 30°2?, step speed 0.06°/3 seconds. Heating to 550°C introduces a variation in mineral intensities of the 14Å and 10 Å peaks with the 7 Å peak greatly reduced or totally removed (Ramm 1991). In addition, slow scan between 24 and 26°2?, with step speed of 0.01/4 seconds was performed on the samples in order to distinguish between kaolinite and chlorite. Kaolinite (001) and chlorite (002) interfere at 7 Å reflection, but in slow scan, the peaks of kaolinite (002) and chlorite (004) basal reflection helps to distinguish the two (Ramm 1991).

Quartz was used as an internal standard since it is present in all samples. The product of peak height and peak width at half its height was taken as the intensity for each recognized mineral. Reflection intensities were measured by the Philips *X'Pert High Score* software program and normalized to the quartz standard at the 3.34 Å peak. Figure 4.5 shows the peaks used in the identification of minerals by XRD bulk analysis and the weight factors used for semi-quantitative analysis.

Mineral	hkl	d Å	Weight Factor
Chlorite	001	14.00	20.0
Illite	001	10.00	-
Muscovite	001	10.00	20.0
Kaolinite	001	7.00	20.0
Total Clay	02 002, 11	4.50	20.0
Quartz	100	4.26	7.5
Quartz	101	3.34	1.0
K – Feldspar	-202, 002, 040	3.24	3.7
Albite	002 040 220	2.28	4.2
Calcite	104	3.04	1.6
Dolomite	104	2.89	-
Ankerite	104	2.90	1.2
Siderite	104	2.79	4.0
Pyrite	200	2.71	2.0

Figure 4.5. Table showing the peaks used in the identification of minerals by XRD bulk analysis and the weight factors used for quantification (Ramm 1991).

All XRD data is available for review in Appendix B.

4.2.3 Net/Gross Estimates Based on Digital Photographs and Logs

Detail digital photographs were taken of the coastal outcrops using a Nikon 4.3 megapixel camera. The digital images were edited using the *Nikon View* software package, and panorama images were created using *ArcSoft Panorama Maker 3.0*.

Net to gross ratio (N/G) is a petroleum industry term used to express the approximate amount of a reservoir which meets the minimum requirements for production: Rocks with adequate porosity and permeability comprise the net portion, where as gross is represented by the total reservoir. This is roughly equivalent to the sand shale ratio, but since some sands are not producible, and some reservoirs are carbonates, the term N/G is used. Sandstones and carbonates typically represent the “producible” (net) part of a reservoir where as silts, clays, mudstones and shales represent the volume of a reservoir which is non-“producible”. Net/Gross values are normally measured in three-dimensions using isopach maps produced from seismic and/or well data. In this study, estimates have been made in two-dimensions using logs and photographs from the cliff sections along the Yorkshire Coast. They will be estimated from a series of ‘pseudo-well-logs’ which have been superimposed on to the digital photographs of selected cliff outcrops. Estimates are intended to show how values within such a fluvial-deltaic environment can vary greatly, dependent upon if the area is dominated by fluvial channels or crevasse splay deposits. The Net/Gross estimates will also be used to compare the potential reservoir qualities of the different depositional environments (channel, crevasse splay and marine).

Net/Gross (N/G) estimates were made by combining field observations and logging with detailed digital photographs of the cliff outcrops which dominate the coast of Yorkshire. Sandstones from channels, crevasse splays, and marine facies will all be considered to meet the minimum requirements for ‘producible’ sands. The overbank mudstones, coals and marine shales will be considered as non-‘producible’. Many of the steep cliff outcrops were inaccessible, and did not allow detail examination or logging. N/G estimates were therefore made using the digital photographs and the typical visible features that the different facies tend to display. For example, the resistive nature of sands compared to that of shales, and differences in vegetation have been used in the estimation of net/gross ratios.

Chapter 5 SEM Results

5.1 SEM Results

A total of 12 samples were analysed using SEM. Samples were analysed to determine degree of sorting, grain calibre, relative amounts of detrital versus authigenic clay and a rough estimate of porosity.

The following set of figures shows a typical representative channel sandstone sample (Figure 5.1), a crevasse splay sandstone (5.2), and a marine sandstone (5.3). Area measurement for each of the above mentioned samples is shown in figure 5.4, 5.5, and 5.6 respectively. A summary of all samples analysed using SEM are shown in section 5.1.4, and all SEM data is available for review in Appendix A.

Yorkshire1

Project: Yorkshire1 Owner: Chris Peltonen Site: Site of Interest 3	Sample: Sample 15 Type: Channel ID: cw4-syc3

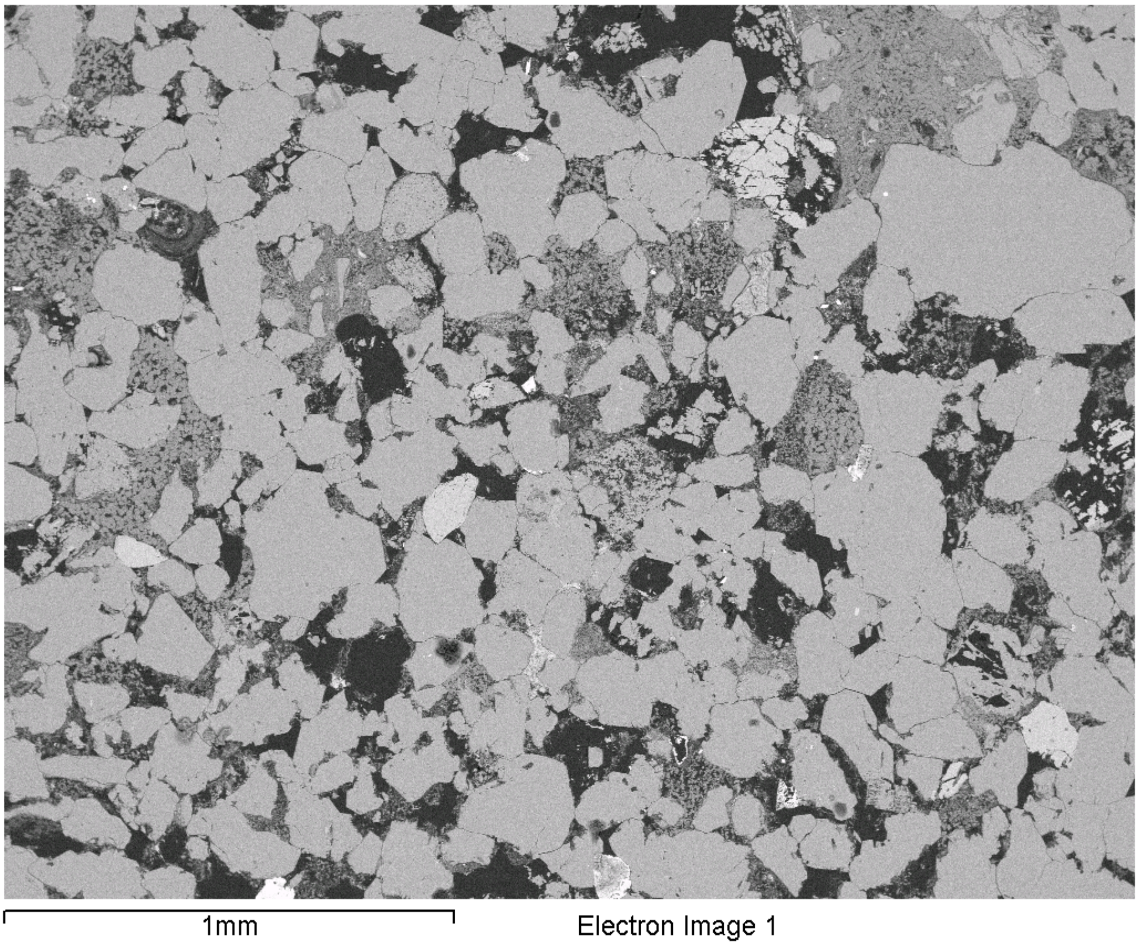


Figure 5.1. Backscatter image of a typical channel sand, Sycarham Member of the Cloughton Formation (CW4-SYC3).

Yorkshire1

Project: Yorkshire1 Owner: Chris Peltonen Site: Site of Interest 4	Sample: Sample 17 Type: Crevasse Splay ID: sw2-1

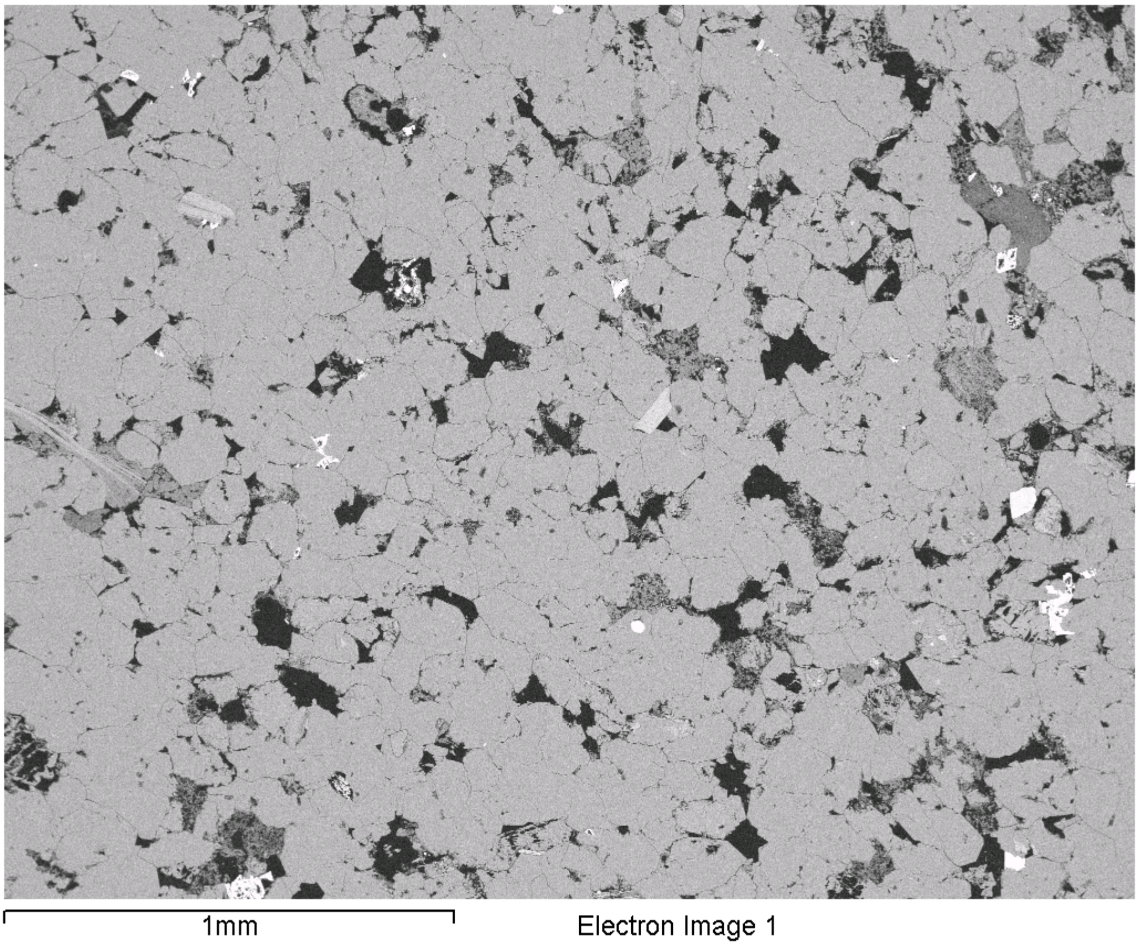


Figure 5.2. Backscatter image of a typical crevasse splay sand, Saltwick Formation (SW1-2).

Yorkshire1

Project: Yorkshire1 Owner: Chris Peltonen Site: Site of Interest 1	Sample: Sample 14 Type: Marine ID: cw5-7

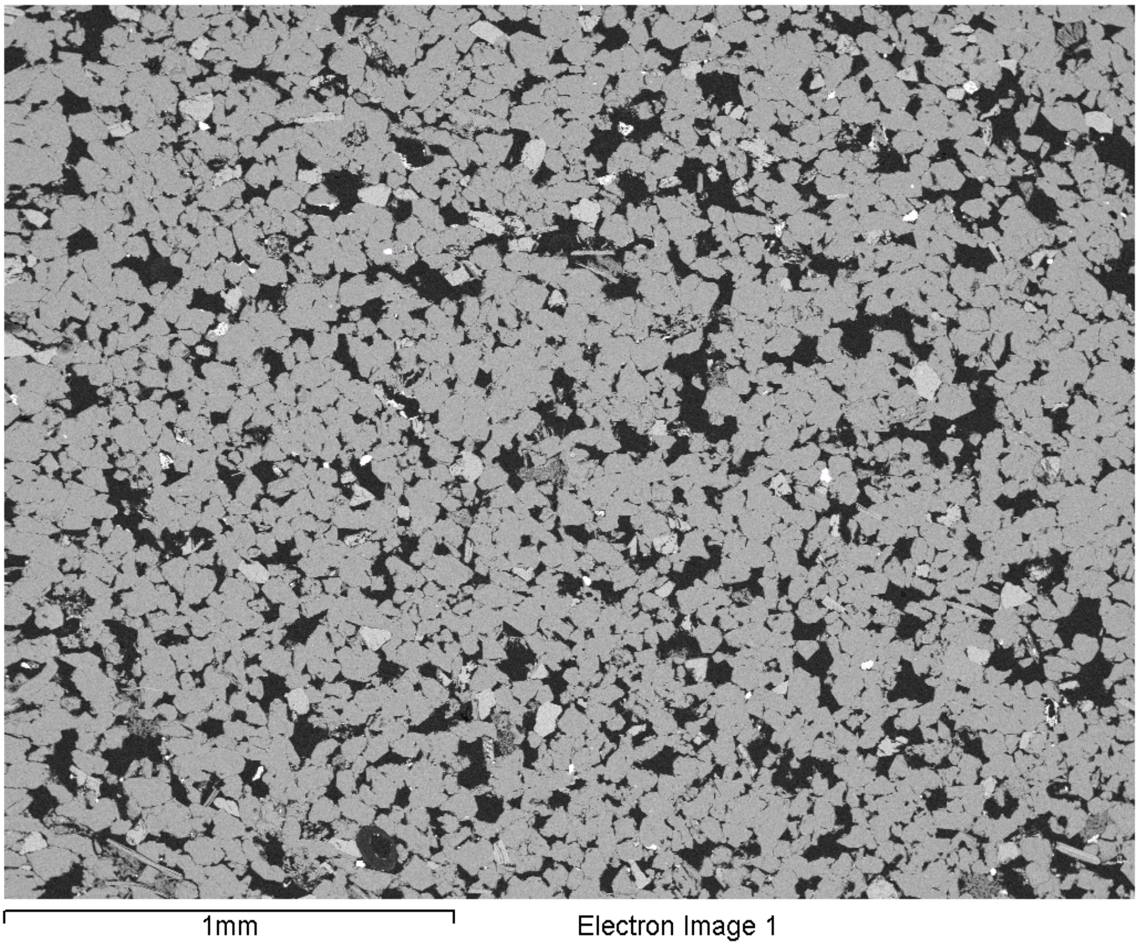


Figure 5.3. Backscatter image of a marine sandstone , Helwath Beck Member of the Scarborough Formation (CW5-7).

Yorkshire1 CW4-SYC3-SITE3

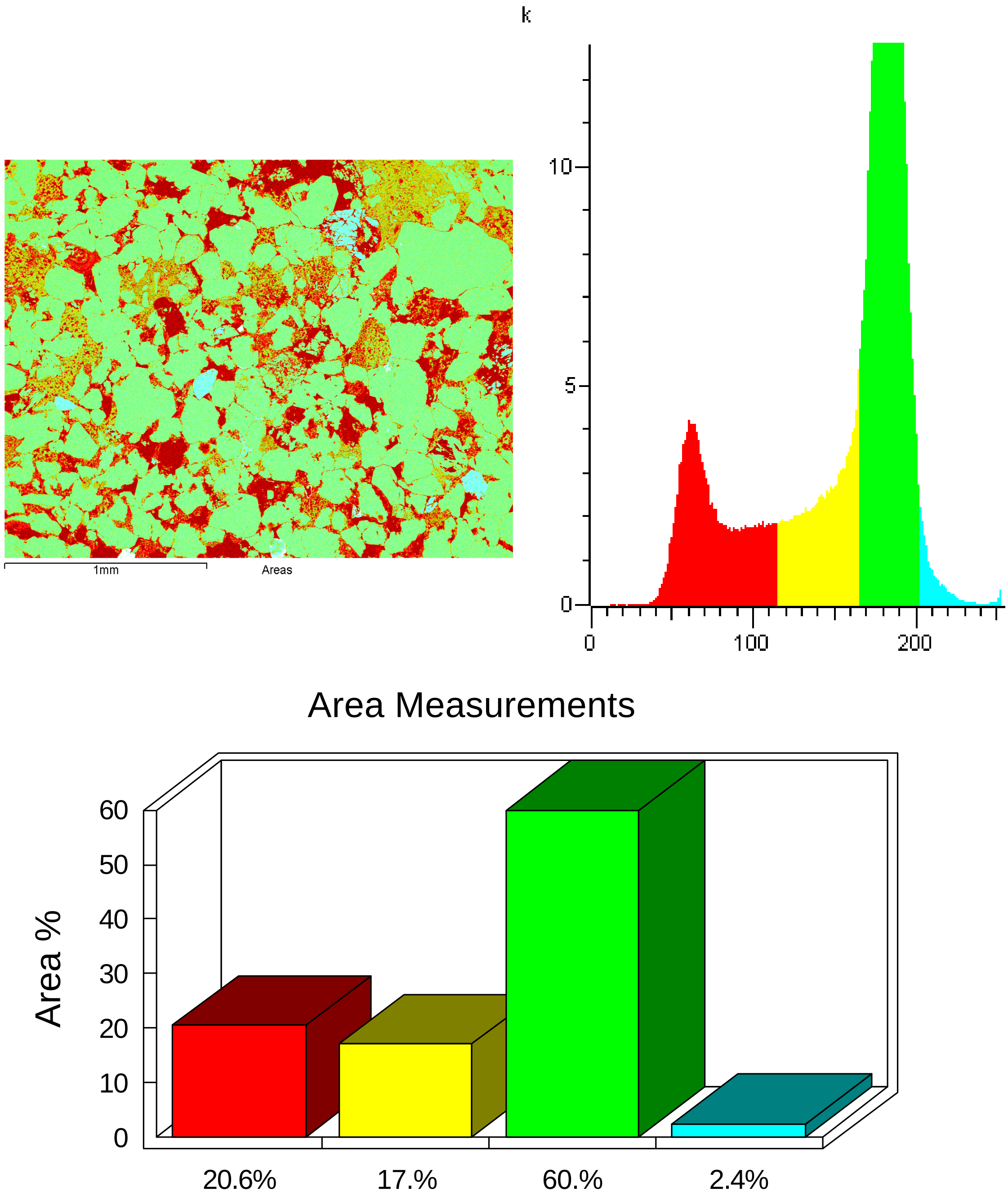
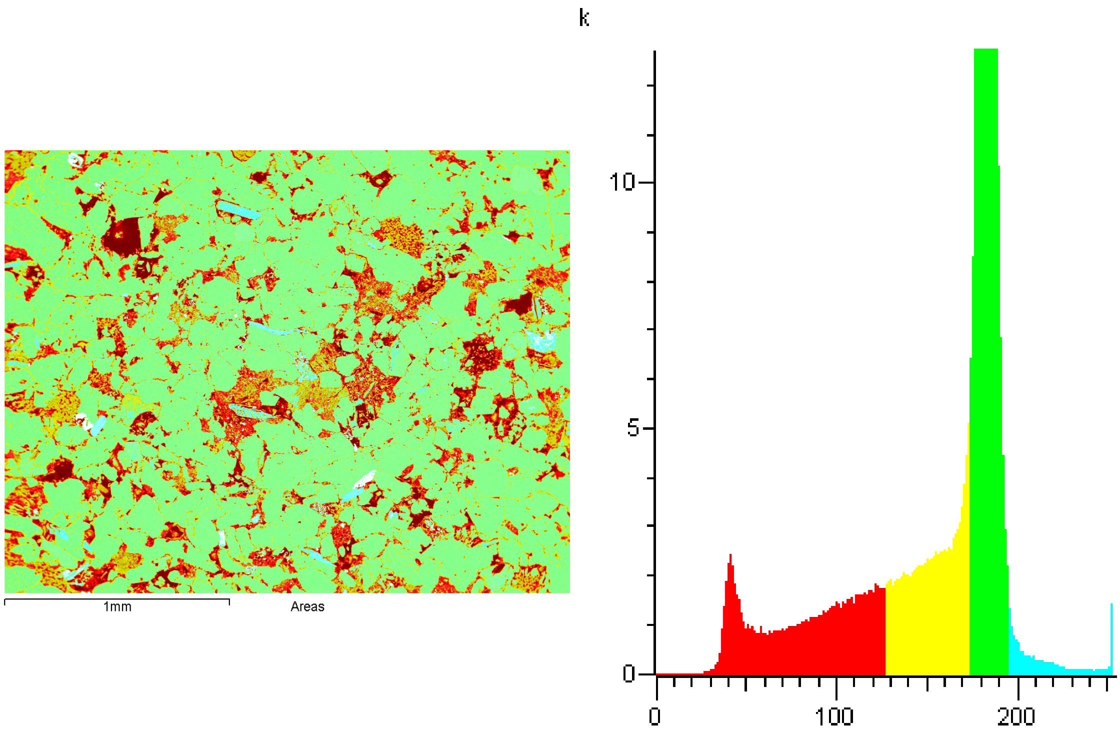


Figure 5.4. Area measurement of a channel sand from the Sycarham Member of the Cloughton Formation (CW4-SYC3). Red = porosity; Yellow = kaolinite; Green = detrital grains; Blue = mica/heavier minerals.

Yorkshire1 SW1-2-SITE4



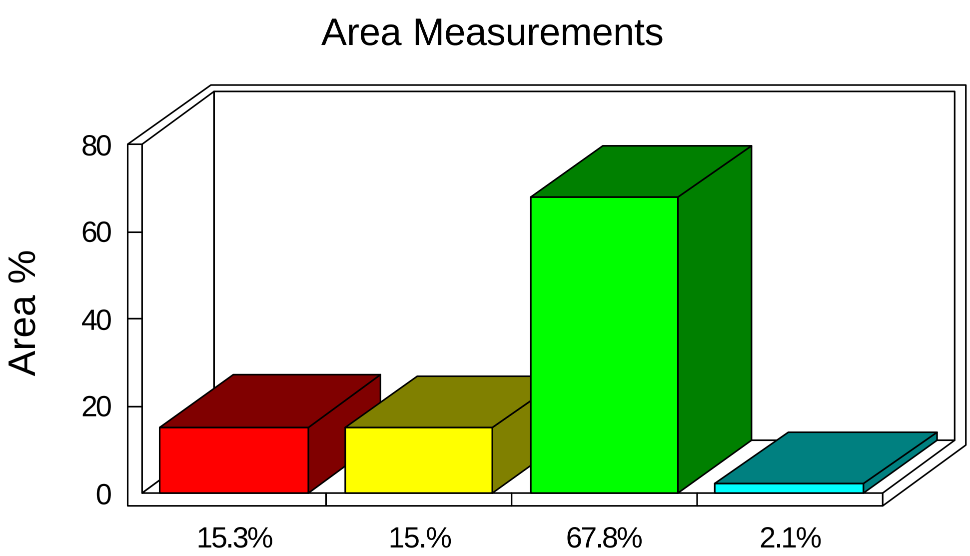


Figure 5.5. Area measurement of a crevasse splay sample from the Saltwick Formation (SW1-2). Red = porosity; Yellow = kaolinite; Green = detrital grains; Blue = mica/heavier minerals.

Yorkshire1 CW5-7-SITE1

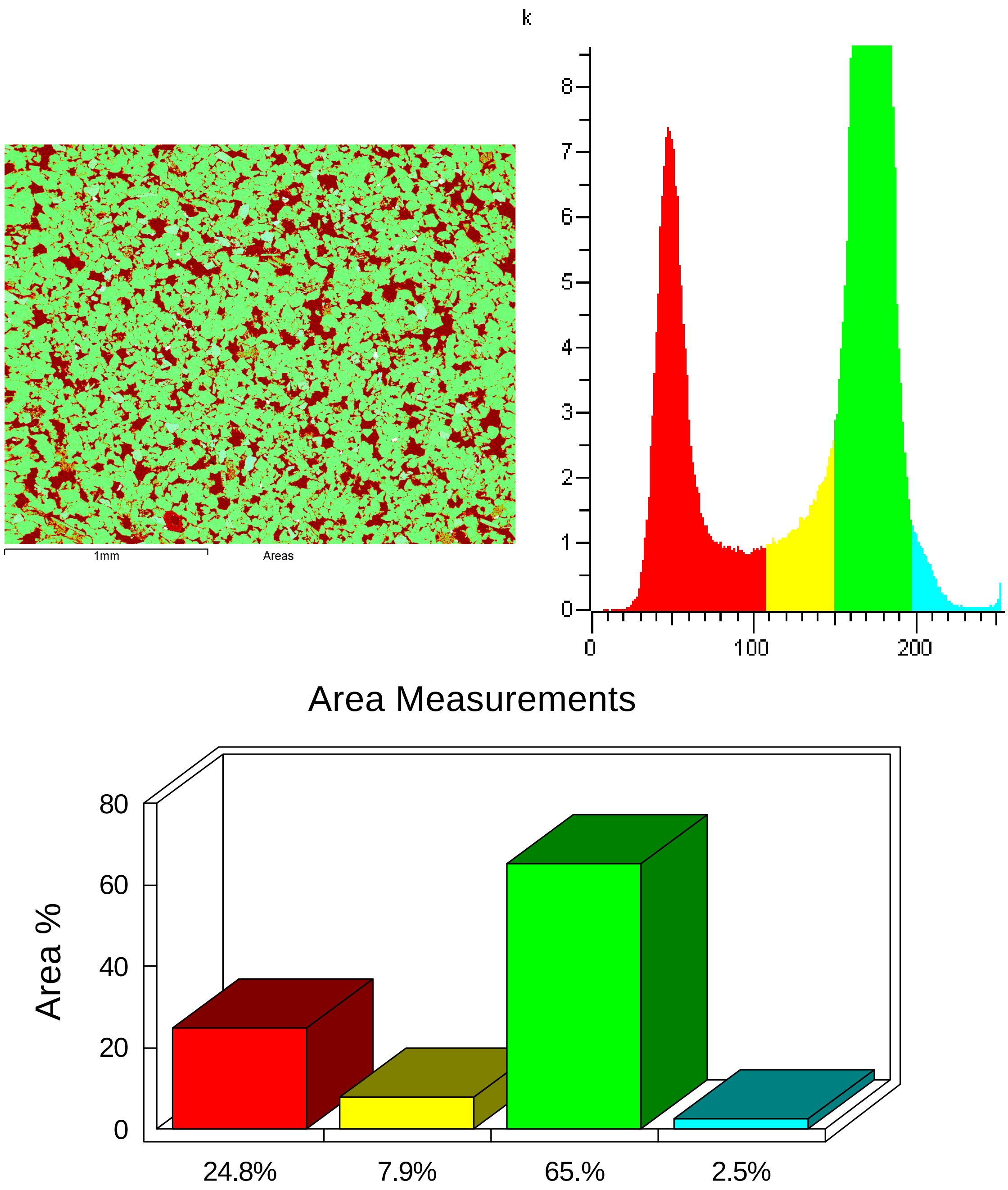


Figure 5.6. Area measurement of a marine sandstone from the Helwath Beck Member of the Scarborough Formation (CW5-7). Red = porosity; Yellow = kaolinite; Green = detrital grains; Blue = mica/heavier minerals.

5.2 Channel Sands

The channel sands display the coarsest median grain size and relatively poor sorting. Abundant authigenic minerals occur with the occurrence of mica being relatively low in comparison to crevasse splay and marine sands. Area measurements conclude that porosity in the channel sandstones has an average of 17.5%, with a low of 13.7% and high of 20.7%. The channel sands have the greatest occurrence of authigenic clays with an average of 17.5%, a low of 14.5% and a high of 23.1%.

FACIES	SAMPLE	SITE	POROSITY*	AUTHIGENIC CLAYS*	DETRITAL GRAINS*	HEAVY MIN'S*
CHANNEL	SW1-1	1	16.7 %	19.4 %	61.7 %	2.2 %
		2	17.1 %	23.1 %	57.2 %	1.5 %
		3	16.6 %	21.6 %	59.2 %	2.0 %
		4	15.2 %	20.2 %	62.1 %	2.1 %
		AVG	*16.4 %*	*21.1 %*	*60.1 %*	*2.0 %*
	SW1-2	1	16.3 %	15.8 %	66.0 %	2.1 %
		2	13.7 %	15.7 %	69.2 %	1.6 %
		3	17.2 %	15.1 %	66.1 %	1.9 %
		4	15.3 %	15.0 %	67.8 %	2.1 %
		AVG	*15.6 %*	*15.4 %*	*67.3 %*	*1.9 %*
	SW3-1	1	14.9 %	19.6 %	63.5 %	2.1 %
		2	16.0 %	16.9 %	64.1 %	3.3 %
		3	15.8 %	18.2 %	63.0 %	3.1 %
		4	19.1 %	17.5 %	61.4 %	1.9 %
		AVG	*16.5 %*	*18.1 %*	*63.0 %*	*2.6 %*
	SCY1-3	1	20.7 %	14.9 %	62.9 %	2.3 %
		2	19.4 %	18.0 %	61.1 %	2.6 %
		3	19.8 %	16.5 %	61.7 %	2.8 %
		4	19.4 %	14.5 %	64.2 %	2.9 %
		AVG	*19.8 %*	*16.0 %*	*62.5 %*	*2.7 %*
	CW4-SYC3	1	18.1 %	16.5 %	60.5 %	4.9 %
		2	20.1 %	16.4 %	60.9 %	2.6 %
		3	20.6 %	17.0 %	60.0 %	2.4 %
		4	16.7 %	16.4 %	63.1 %	4.1 %
		AVG	*18.9 %*	*16.6 %*	*61.1 %*	*3.5 %*

Figure 5.7. Table summarizing results of backscatter area measurements of channel sandstones.

5.3 Crevasse Splay Sands

As seen in figure 5.2, the typical crevasse splay sand displays a overall finer median grain size compared to the channel sands. They tend to be better sorted but have a greater fraction of micas. Area measurements show similar porosity values as the channel sands with an average of 16.9%, a low of 9.7% and a high of 22.5%. The amount of authigenic clay is consistently lower than that of the channel sands with an average of 9.7%, a low of 7.2% and a high of 11.4%.

FACIES	SAMPLE	SITE	POROSITY*	AUTHIGENIC CLAYS	DETRITAL GRAINS*	HEAVY MIN'S*
CREVASSE	CW1-4	1	20.8 %	11.4 %	64.1 %	3.0 %
		2	21.2 %	11.4 %	62.2 %	4.8 %
		3	19.2 %	9.6 %	66.8 %	3.9 %
		4	18.8 %	9.6 %	67.3 %	3.8 %
		AVG	*20.0 %*	*10.5 %*	*65.1 %*	*3.9 %*
	CW1-7	1	22.5 %	10.1 %	62.8 %	4.3 %
		2	21.8 %	9.8 %	65.5 %	2.6 %
		3	19.7 %	11.3 %	66.0 %	2.9 %
		4	21.1 %	9.4 %	65.7 %	4.1 %
		AVG	*21.3 %*	*10.2 %*	*65.0 %*	*3.5 %*
	SYC1-1	1	16.7 %	7.6 %	74.0 %	2.1 %
		2	18.8 %	9.1 %	69.9 %	2.7 %
		3	17.8 %	7.9 %	72.8 %	1.8 %
		4	16.5 %	7.2 %	75.5 %	1.2 %
		AVG	*17.5 %*	*8.0 %*	*73.1 %*	*2.0 %*
	SW2-1	1	11.2 %	9.2 %	77.2 %	3.0 %
		2	10.5 %	9.7 %	78.7 %	2.1 %
		3	9.7 %	8.5 %	80.7 %	1.7 %
		4	10.4 %	8.9 %	79.0 %	1.8 %
		AVG	*10.5 %*	*9.1 %*	*78.9 %*	*2.2 %*
	SCY-LN1-5	1	17.3 %	10.8 %	70.8 %	1.9 %
		2	16.7 %	10.8 %	70.6 %	2.7 %
		3	12.8 %	11.1 %	72.5 %	3.7 %
		4	14.8 %	9.2 %	73.4 %	2.9 %
		AVG	*15.4 %*	*10.5 %*	*71.8 %*	*2.8 %*

Figure 5.8. Table summarizing results of backscatter area measurements of crevasse splay sandstones.

5.4 Marine Sands

The main focus of this study was to compare the properties of channel sand versus crevasse splay deposits. For that reason only a two marine samples were analyzed. As seen in figure 5.3, the marine sandstones display the finest and best sorted samples (where not destroyed by bioturbation). Due to the relative small number of samples accurate averages were non-obtainable. There was a varying degree of porosity with some very high numbers. The average porosity for the two samples analysed was 20.5%, with a low of 14.5% and a high of 26.5%. The authigenic clay fraction varied from a low of 6.9% and a high of 14.6% with an average of 10.4%.

FACIES	SAMPLE	SITE	POROSITY*	AUTHIGENIC CLAYS*	DETRITAL GRAINS*	HEAVY MIN'S*
MARINE	EB1-2	1	15.6 %	14.6 %	68.6 %	0.7 %
		2	14.5 %	14.4 %	69.7 %	0.9 %
		3	15.5 %	11.7 %	71.6 %	0.6 %
		4	18.4 %	10.8 %	68.8 %	1.3 %
		AVG	*16.0 %*	*12.9 %*	*69.7 %*	*0.9 %*
	CW5-7	1	24.8 %	7.9 %	65.0 %	2.5 %
		2	26.5 %	6.9 %	65.0 %	2.1 %
		3	24.4 %	7.3 %	66.5 %	2.4 %
		4	23.6 %	8.9 %	65.1 %	3.2 %
		AVG	*24.8 %*	*7.8 %*	*65.4 %*	*2.6 %*

Figure 5.9. Table summarizing results of backscatter area measurements of marine sandstones.

5.5 Summary

The following figures 5.10 and 5.11 provide an overall summary of all SEM area measurement results.

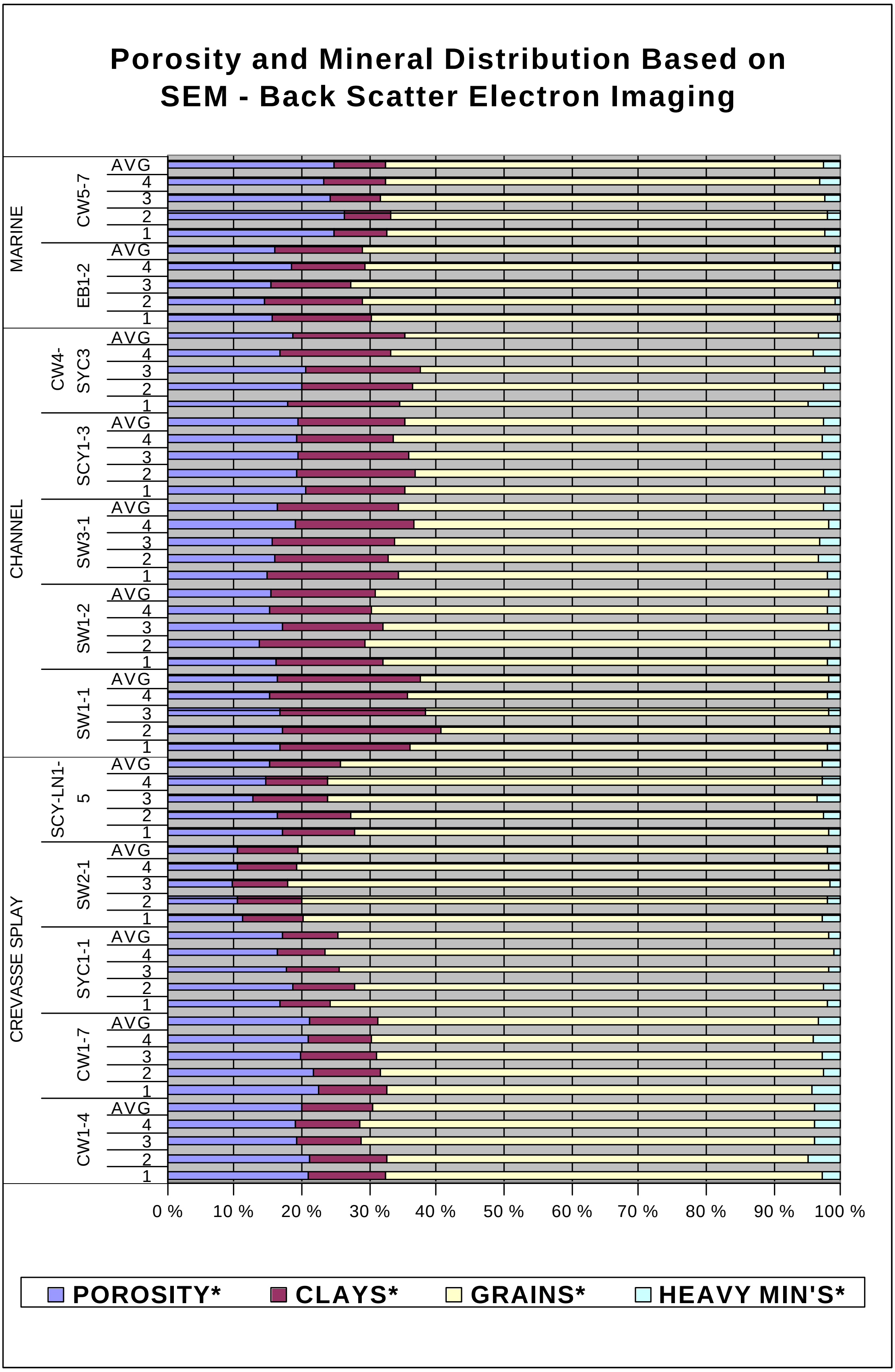


Figure 5.10. Graphic presentation of backscatter area measurements results.

FACIES	SAMPLE	SITE	POROSITY*	AUTHIGENIC CLAYS*	DETRITAL GRAINS*	HEAVY MIN'S*
CREVASSE SPLAY	CW1-4	1	20,8 %	11,4 %	64,1 %	3,0 %
		2	21,2 %	11,4 %	62,2 %	4,8 %
		3	19,2 %	9,6 %	66,8 %	3,9 %
		4	18,8 %	9,6 %	67,3 %	3,8 %
		AVG	*20,0 %*	*10,5 %*	*65,1 %*	*3,9 %*
	CW1-7	1	22,5 %	10,1 %	62,8 %	4,3 %
		2	21,8 %	9,8 %	65,5 %	2,6 %
		3	19,7 %	11,3 %	66,0 %	2,9 %
		4	21,1 %	9,4 %	65,7 %	4,1 %
		AVG	*21,3 %*	*10,2 %*	*65,0 %*	*3,5 %*
	SYC1-1	1	16,7 %	7,6 %	74,0 %	2,1 %
		2	18,8 %	9,1 %	69,9 %	2,7 %
		3	17,8 %	7,9 %	72,8 %	1,8 %
		4	16,5 %	7,2 %	75,5 %	1,2 %
		AVG	*17,5 %*	*8,0 %*	*73,1 %*	*2,0 %*
	SW2-1	1	11,2 %	9,2 %	77,2 %	3,0 %
		2	10,5 %	9,7 %	78,7 %	2,1 %
		3	9,7 %	8,5 %	80,7 %	1,7 %
		4	10,4 %	8,9 %	79,0 %	1,8 %
		AVG	*10,5 %*	*9,1 %*	*78,9 %*	*2,2 %*
	SCY-LN1-5	1	17,3 %	10,8 %	70,8 %	1,9 %
		2	16,7 %	10,8 %	70,6 %	2,7 %
		3	12,8 %	11,1 %	72,5 %	3,7 %
		4	14,8 %	9,2 %	73,4 %	2,9 %
		AVG	*15,4 %*	*10,5 %*	*71,8 %*	*2,8 %*
CHANNEL	SW1-1	1	16,7 %	19,4 %	61,7 %	2,2 %
		2	17,1 %	23,1 %	57,2 %	1,5 %
		3	16,6 %	21,6 %	59,2 %	2,0 %
		4	15,2 %	20,2 %	62,1 %	2,1 %
		AVG	*16,4 %*	*21,1 %*	*60,1 %*	*2,0 %*
	SW1-2	1	16,3 %	15,8 %	66,0 %	2,1 %
		2	13,7 %	15,7 %	69,2 %	1,6 %
		3	17,2 %	15,1 %	66,1 %	1,9 %
		4	15,3 %	15,0 %	67,8 %	2,1 %
		AVG	*15,6 %*	*15,4 %*	*67,3 %*	*1,9 %*
	SW3-1	1	14,9 %	19,6 %	63,5 %	2,1 %
		2	16,0 %	16,9 %	64,1 %	3,3 %
		3	15,8 %	18,2 %	63,0 %	3,1 %
		4	19,1 %	17,5 %	61,4 %	1,9 %
		AVG	*16,5 %*	*18,1 %*	*63,0 %*	*2,6 %*
	SCY1-3	1	20,7 %	14,9 %	62,9 %	2,3 %
		2	19,4 %	18,0 %	61,1 %	2,6 %
		3	19,8 %	16,5 %	61,7 %	2,8 %
		4	19,4 %	14,5 %	64,2 %	2,9 %
		AVG	*19,8 %*	*16,0 %*	*62,5 %*	*2,7 %*
	CW4-SYC3	1	18,1 %	16,5 %	60,5 %	4,9 %
		2	20,1 %	16,4 %	60,9 %	2,6 %
		3	20,6 %	17,0 %	60,0 %	2,4 %
		4	16,7 %	16,4 %	63,1 %	4,1 %
		AVG	*18,9 %*	*16,6 %*	*61,1 %*	*3,5 %*
MARINE	EB1-2	1	15,6 %	14,6 %	68,6 %	0,7 %
		2	14,5 %	14,4 %	69,7 %	0,9 %
		3	15,5 %	11,7 %	71,6 %	0,6 %
		4	18,4 %	10,8 %	68,8 %	1,3 %
		AVG	*16,0 %*	*12,9 %*	*69,7 %*	*0,9 %*
	CW5-7	1	24,8 %	7,9 %	65,0 %	2,5 %
		2	26,5 %	6,9 %	65,0 %	2,1 %
		3	24,4 %	7,3 %	66,5 %	2,4 %
		4	23,6 %	8,9 %	65,1 %	3,2 %
		AVG	*24,8 %*	*7,8 %*	*65,4 %*	*2,6 %*

Chapter 6 XRD Results

6.1 XRD Results

A total of thirteen samples were analysed using XRD. Five of these were analysed for both whole-rock (bulk) and clay fraction with the remaining eight only being analysed for bulk composition. Original results are available for review in Appendix B.

Initial results showed that the clay fraction was dominated by kaolinite and mica with only a rare or non occurrence of illite, chlorite and smectite. It was not the goal of this project to do a detailed examination of the clay fraction. The goal of XRD analysis was to investigate the relative amounts of potassium feldspar and authigenic kaolinite, in order to discuss the degree of dissolution and precipitation of these respective minerals as a result of meteoric water flushing (process to be discussed in the following chapter). This was possible to show without running clay fraction analysis. Bulk analysis provided accurate values for the potassium feldspar content (bulk-slow scan) and a relative value for kaolinite. Kaolinite can be very difficult to accurately quantify due to the interference of chlorite and its varying crystallinities, i.e. dickite (Ramm 1991). Although there was some variation in kaolinite values, the channel sandstones were completely free of potassium feldspars, concluding a greater degree of meteoric water flushing and the leaching of potassium feldspars occurred there. This alone provided adequate results to discuss the effects of meteoric water flushing, and eliminated the need for detailed analysis of the clay fraction in order to determine true kaolinite amounts. This will be discussed in further detail in the following chapter, but it is necessary to explain the process of acquiring results before presenting them.

6.1.1 Clay Analysis

As mentioned above, clay analysis was only performed on five of the XRD samples. Untreated clay analysis showed the presence of chlorite in only one sample (SW1-2, Saltwick Formation channel sandstone) (Figure 6.1). Slow scan was performed and confirmed the presence of chlorite in SW1-2, and showed trace amounts in SW1-1 (Saltwick Formation channel sandstone) and CW1-7 (Gristhorpe Member crevasse splay) (Figure 6.2). The samples were treated with ethylene glycol and results showed no indications of smectite (Figure 6.3). Mica/illite content was relatively consistent throughout the samples.

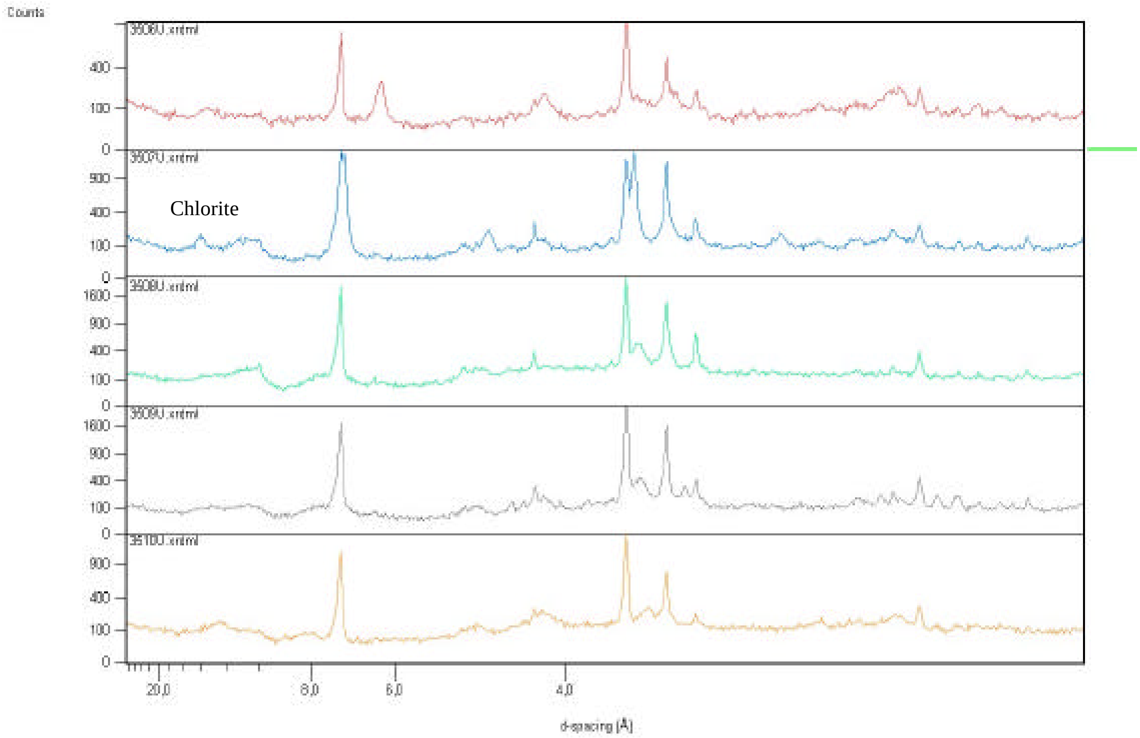


Figure 6.1. Summary of XRD clay analysis.

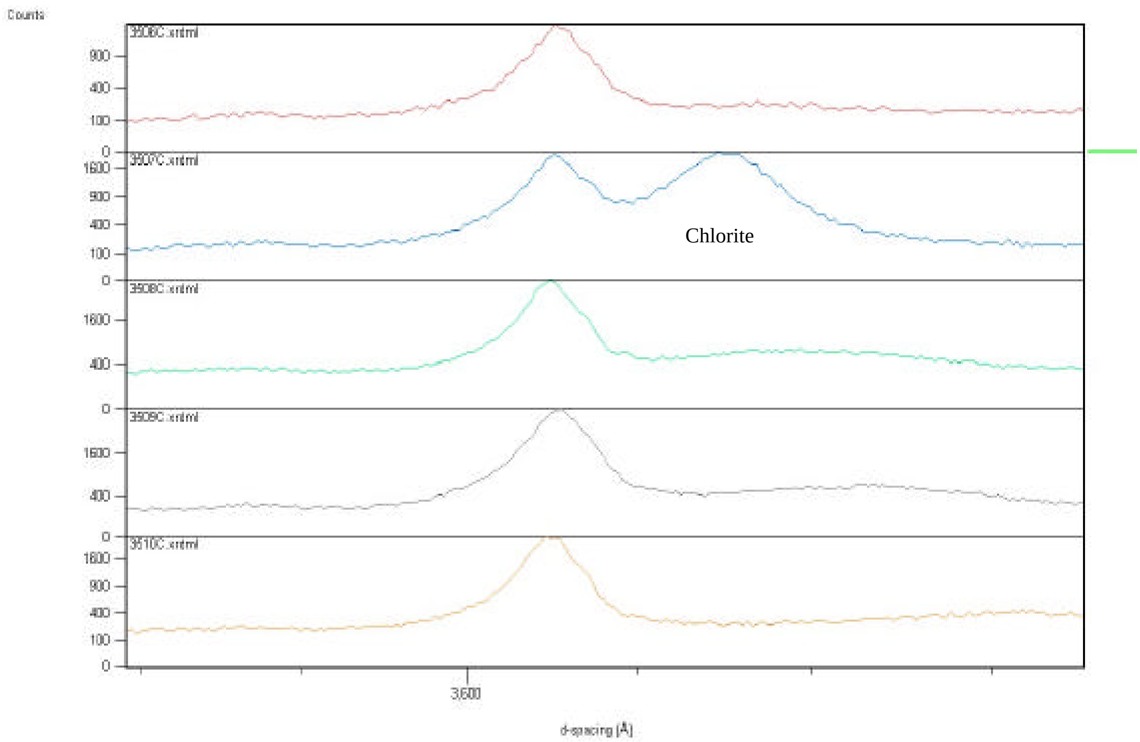


Figure 6.2. Summary of XRD clay analysis.

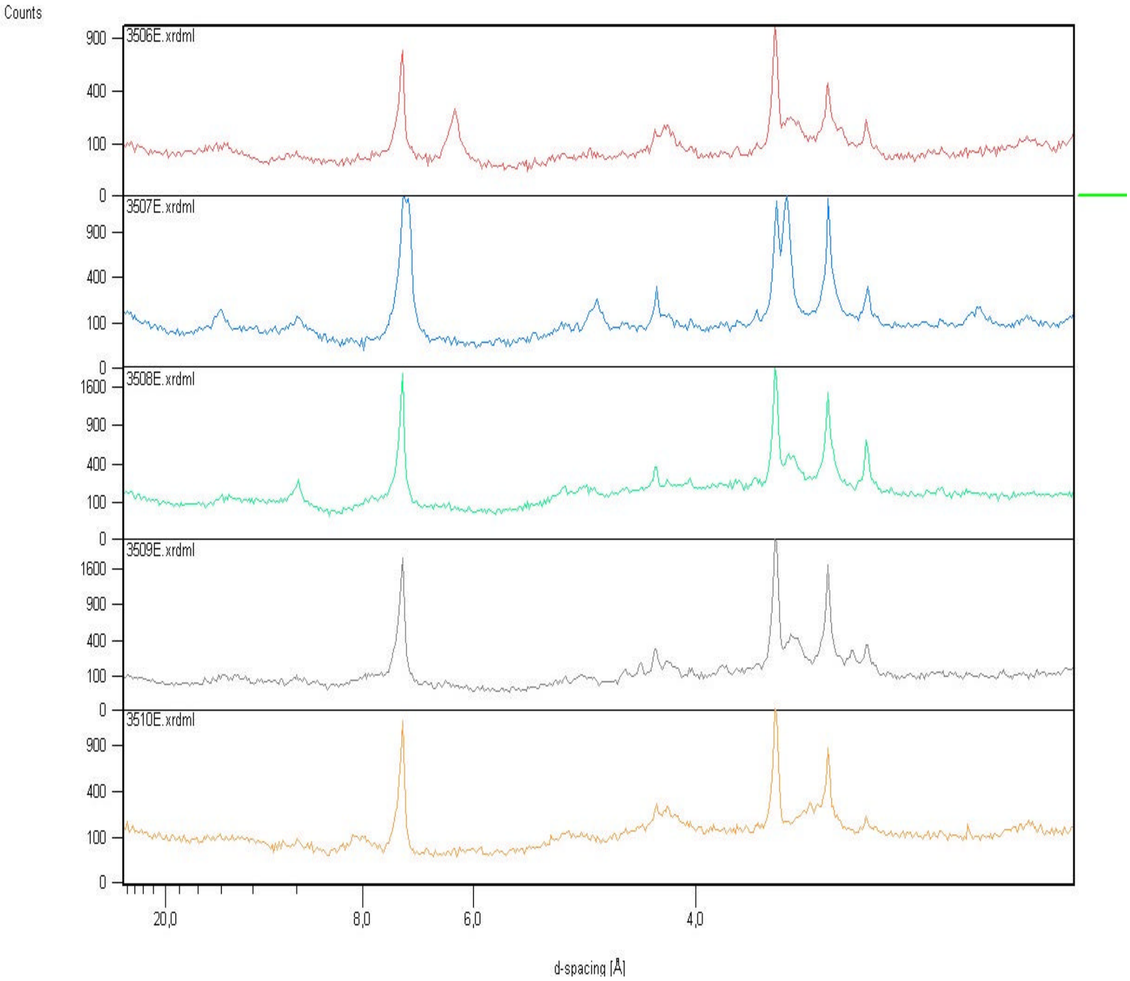


Figure 6.3. Summary of XRD-ethylene glycolated samples.

6.1.2 Bulk Analysis

All 13 samples were analyses for bulk composition. Results with respect to relative amounts of potassium feldspar and kaolinite are summarized in the table in Figure 6.4, and graphically represented in Figure 6.5.

FACIES	SAMPLE #	KAOLINITE	K-FELDSPAR
CREVASSE SPLAY	CW1-4	5,58%	6,13%
	CW1-7	3,86%	1,09%
	SYC1-1	10,03%	1,94%
	SW2-1	4,68%	5,71%
	SCY-LN1-5	11,21%	4,24%
CHANNEL	SW1-1	11,06%	0.00
	SW1-2	24,86%	0.00
	SW3-1	14,93%	0.00
	SCY1-3	15,40%	0.00
	CW4-SYC3	4,32%	0.00
MARINE	EB1-2	3,02%	0.00
	CW5-7	1,93%	4,79%
	CW3-LB1	22,28%	3,88%

Figure 6.4. Summary of XRD bulk composition values for kaolinite and k-feldspar; based on standardized peaks and weight factors from Ramm, 1991.

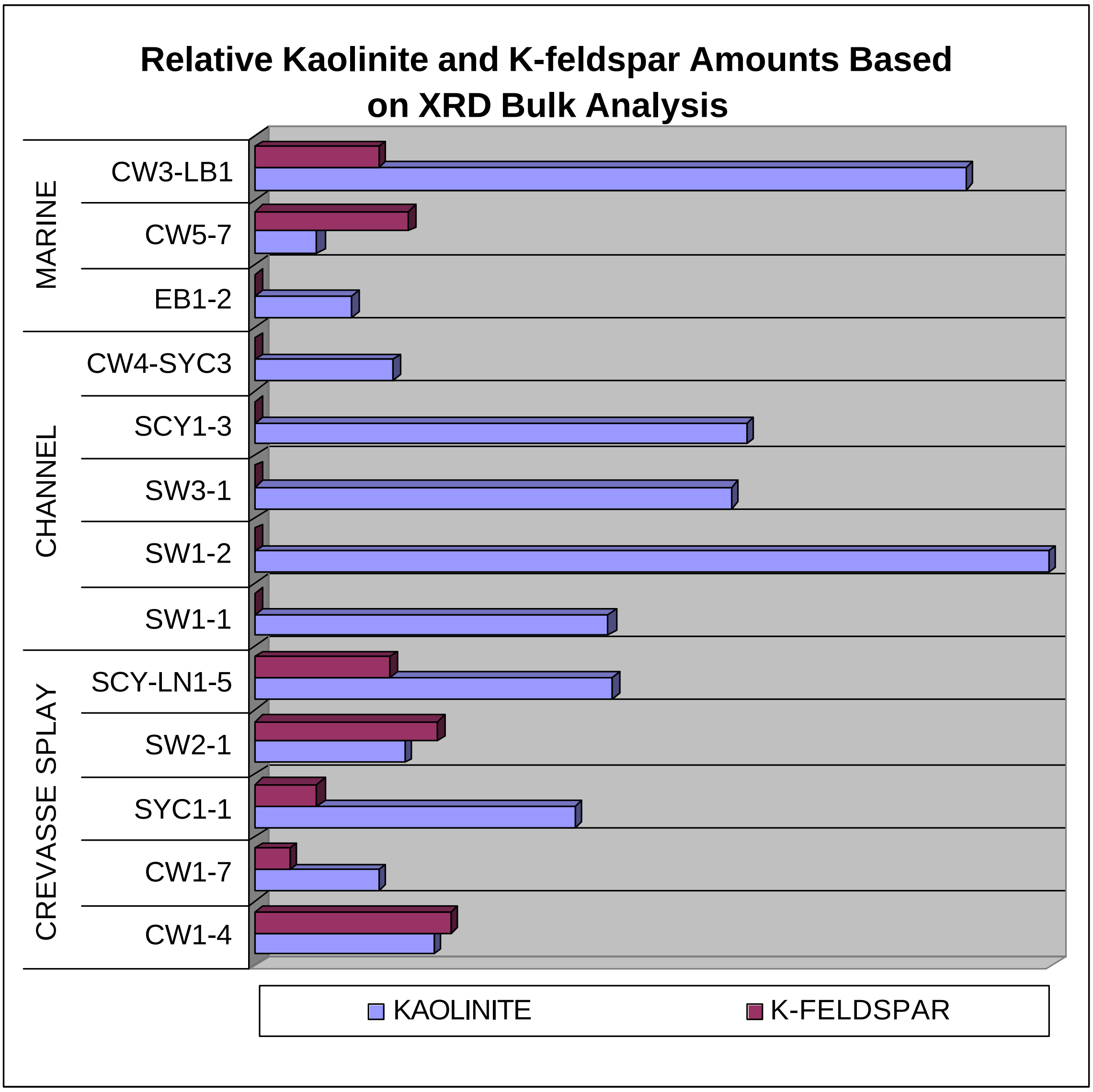


Figure 6.5. Graphical representation of XRD bulk analysis results for kaolinite and k-feldspar.

6.2 Channel Sands

Five of the samples processed were from channel sandstones. XRD results for these channel sandstone samples showed a definite pattern with respect to potassium feldspar and kaolinite content. Potassium feldspar was not found in any of the samples and values for kaolinite were generally greater than those from crevasse splay and marine sandstones samples. Kaolinite values ranged from a high of 25% and a low of 4% with an average of 14.3%.

6.3 Crevasse Splay Sands

Five of the samples processed were crevasse splay sandstones. Results with respect to relative potassium feldspar and kaolinite amounts were not as straight forward as those from the channel sandstone facies. Some of the samples had higher amounts of kaolinite than potassium feldspar, but all samples did contained detectable amounts of potassium feldspar, indicating a consistent characteristic difference between the channel and crevasse splay sandstones.

Values for potassium feldspar varied between a high of 6% and a low of 1% with an average of 4%. Kaolinite amounts were slightly higher with values ranging from 4 to 11% and an average of 7%.

6.4 Marine Sands

The primary goal for XRD analysis was to compare the relative amounts of potassium feldspar versus kaolinite within the channel and crevasse splay sandstones. For this reason only a few (3) marine sandstone samples were analysed. Due to a greater degree of reworking, shallow marine sandstone are expected to show less consistent values with respect to potassium feldspar and kaolinite as a function of meteoric water flushing. Results will be briefly discussed in the following chapters.

Values for potassium feldspar varied between 0 and 5%, and kaolinite amounts ranged from 2 to 22%.

Chapter 7 Net/Gross Estimates

7.1 Introduction

As described in section 4.2.3, digital photographs and lithostratigraphic logs were used to estimate net to gross ratios for a selection of cliff outcrops in Yorkshire. Estimates have been completed for the three main facies (channel sandstones, crevasse splay sandstones and marine sandstones) and are presented below.

7.2 Channel Sandstones

Channel-facies sandstones crop out as individual or interconnected channels. They tend to have elongated, ribbon-like form and are enclosed within fine grained floodplain facies sediments. Occasionally the channels occur as stacked, interconnected outcrops but more often they occur as individual, isolated channels.

The first two N/G estimates are from Whitby: One represents an outcrop dominated by stacked fluvial channels with only occasional siltstones and very rare mudstones (abandoned channel clay-plug), and the other outcrop is dominated by floodplain mudstones and crevasse splay sands. Whitby bay is dissected by a south, south-west to north, north-east running normal fault (Figure 7.1). This fault has an estimated offset of 12 meters, and appears to have been active through out the deposition of the Saltwick and Eller Beck and stopped sometime during the deposition of the Sycarham Member. A cross-section of the Whitby area and represented formations can be seen in figure 7.1. The following figure, 7.2, shows the floodplain and crevasse splay dominated outcrop which lies to the east of the Whitby fault and figure 7.3 is the cliff section to the west of the Whitby fault which is dominated by stacked channels deposits

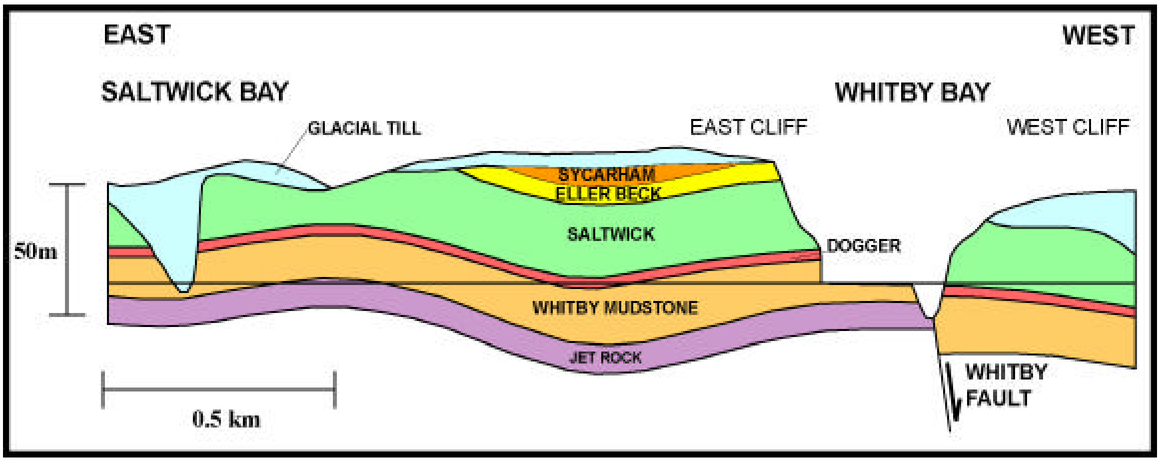


Figure 7.1. Cross-section of the Whitby area

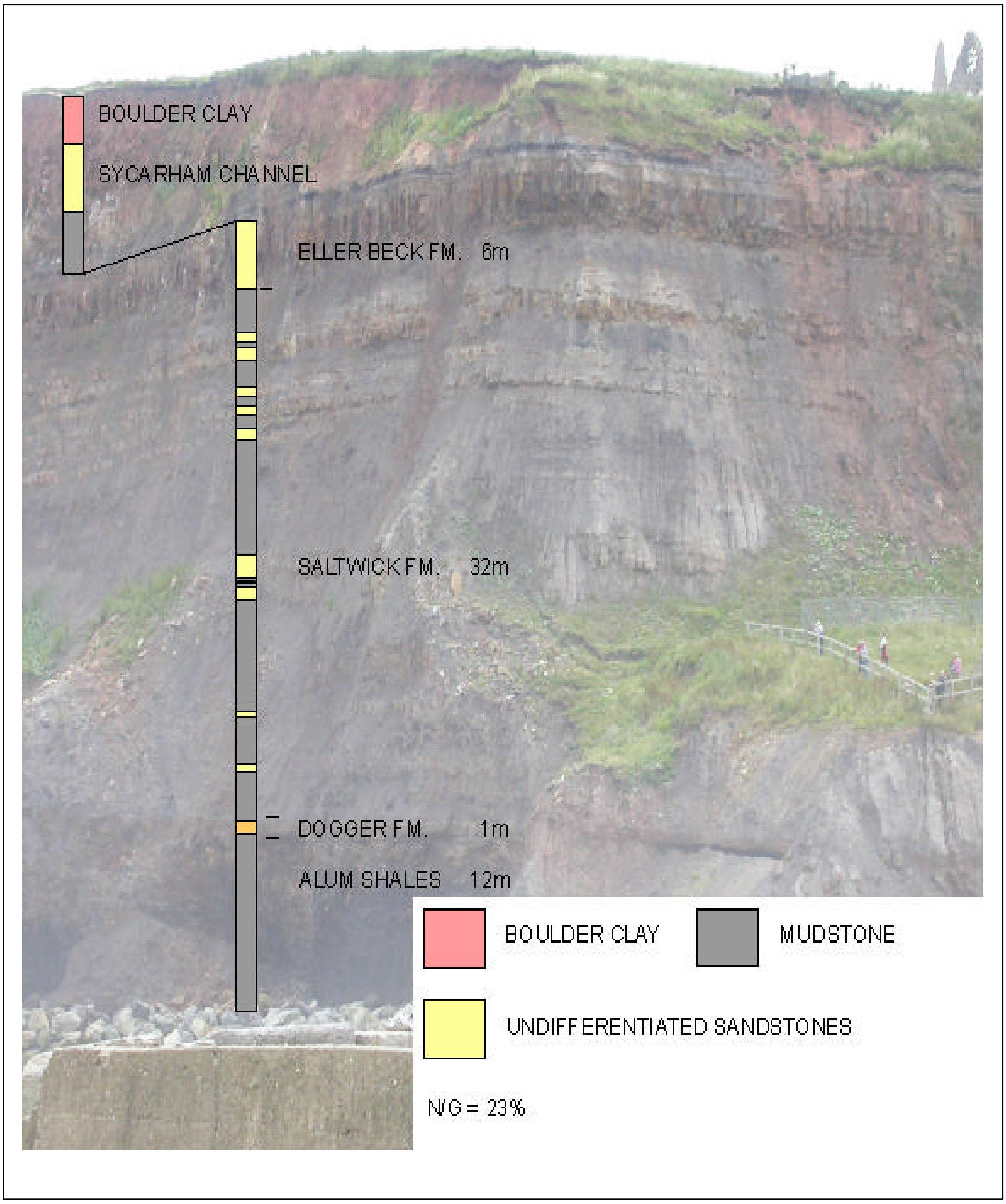


Figure 7.2. Whitby East; immediately adjacent to the Whitby fault showing the distribution of sediments dominated by mudstones with occasional crevasse splay deposits, and topped by a channel incision of the Sycarham member. Net to gross ratio for this 60 meter section was estimated at 23%.

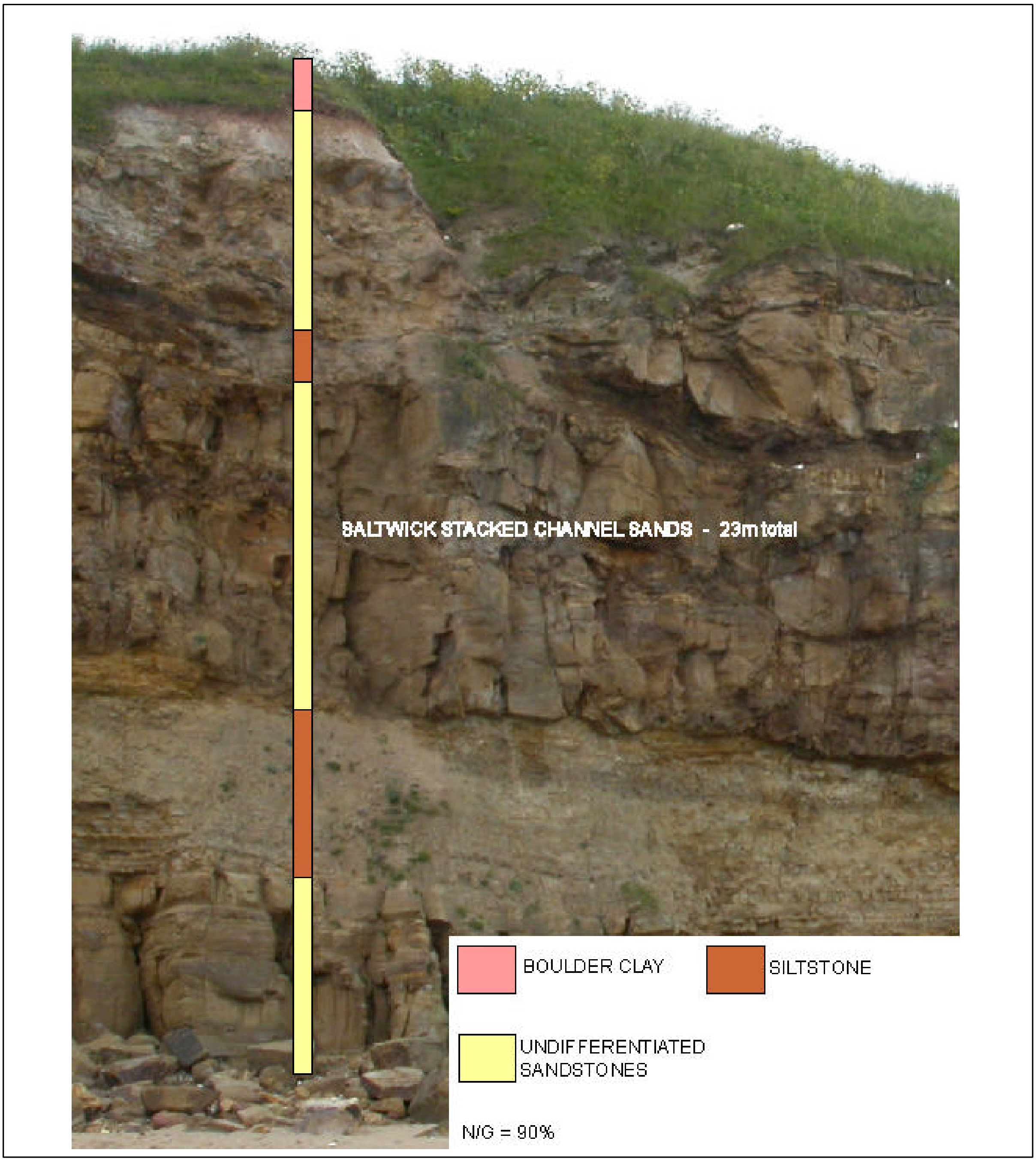


Figure 7.3.Whitby west; immediately west of the Whitby Fault showing that the sediments are predominantly made up of stacked channel sand deposits with minor interfluvial mudstones and siltstones. Net to Gross ratio was estimated for this 23 meter section to be 72%.

7.2.1 Discussion of Whitby N/G Estimates

These depositional differences can be attributed to fault controlled channel and sediment distribution. It is possible that faulting created small vertical relief and slight tilting which resulted in the concentration of, and stacking of fluvial channels to the western side of the Whitby fault. Sediment loading and compaction may have enhanced this tilting and faulting, and helped to confine the migration of fluvial channels. It is interpreted that the vertical relief along the paleo-Whitby fault was substantial enough to limit the migration of the fluvial channel across it, but it did not hinder the deposition of crevasse splay deposits. The east side of the Whitby fault is completely absent of channel deposits until the successions reaches the Sycarham member where there is evidence of a large channel incision. This indicates that the paleo-Whitby fault was active and hindered migration of channels across it through to this time period, but at some time during the deposition of the Sycarham member, this was no longer a controlling factor in channel migration.

This location provides the opportunity to compare a stacked channel dominated sequence and a crevasse splay/floodplain dominated sequence. It is obvious that this local variation will have significant consequences on overall reservoir N/G estimates, and reservoir qualities. In figure 7.3 (west) the N/G ratio for the stacked channel outcrop was estimated at 90%, whereas in figure 7.2 (east) the N/G ratio for the crevasse splay/floodplain sequence was estimated at 23%. Whitby west exemplifies a good potential source rock, but just on the other side of the fault, the sequence has poor if no reservoir potential at all.

The Whitby fault not only led to vertical offset, but also contributed to a dramatic lateral variation in facies. This is an important factor to consider when dealing with fluvial-delta plain depositional environments, because as seen in this example, it could have significant implications on reservoir calculations such as size and N/G.

This example at Whitby west, is one of the only times we see a relatively thick section of continuous, stacked channel sands. The rest of the non-marine deposits of the Ravenscar Group tend to be dominated by overbank fines, as seen on the east side of the fault. Although this is a stacked channel sequence has a good potential reservoir quality, it is important to remember that the total offset of the Whitby fault is only 12 meters and that this would probably not be visible on seismic data.

The following figure, 7.4, is another example of sand to shale ratios found in the non-marine units of the Ravenscar Group. This outcrop is located approximately 2 km north of Cloughton Wyke in an area called Rodger Trod. This cliff section displays deposits from the Sycarham member up to the Moor Grit member of the Scalby formation. The ‘pseudo-well’ was placed ideally to intersect the channel sand within the Sycarham member and maximize the N/G estimate. This figure demonstrates how the N/G estimates can vary drastically laterally. Channel deposits, like the one seen here being intersected, are not very common within the older non-marine units of the Ravenscar Group (Saltwick formation, Sycarham member and Gristhorpe member). In fact, along the stretch of coastline from Cloughton Wyke to Hundale Point, which is a distance of approximately 3 kilometers, there is evidence of only a few of these channels deposits. The remaining deposits are predominantly overbank fines with common crevasse splay deposit.

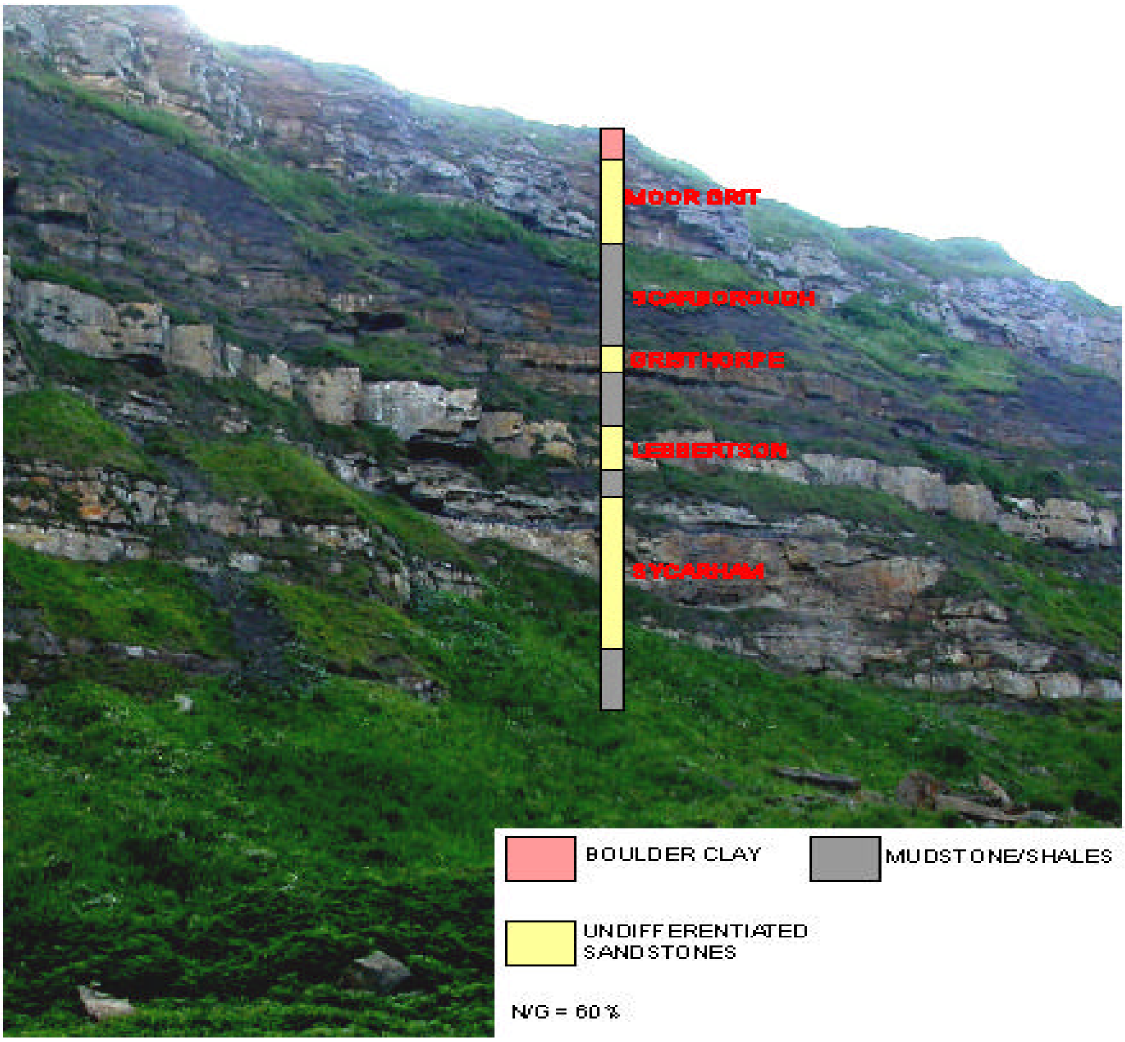


Figure 7.4. N/G estimate from a cliff section approximately 2 km north of Cloughton Wyke.

This sparse distribution of channel sands consequentially leads to poor reservoir potential. As for the older non-marine units of the Ravenscar Group (Saltwick formation, Sycarham member, and Gristhorpe member), the only place where we see a significant volume of channel sands, is in the previous mentioned example of Whitby west. This demonstrates that without some type of control on the distribution of channel deposits, like that exerted by the Whitby fault, these older non-marine units are too random and sparse to have adequate sand to shale ratios to be considered good potential reservoir rocks. It can be said that these units are predominantly overbank fines, with common crevasse splay deposits and only occasional channel deposits. This may be partly due to the fact that during Middle Jurassic uplift, the thick sequence of Lower Jurassic mudstones was eroded first, and re-deposited during the deposition of these channel sands. It is apparent by the sparse distribution of channel sandstones that mudstones made up the dominant fraction of sediment supply during the deposition of these early Ravenscar Group non-marine units.

As for the youngest of the non-marine units, the Scalby formation, there is evidence for a greater degree of channel stacking, and higher sand to shale ratios. This is possibly due to an increase in sand supply, as the surrounding highs have been depleted of Lower Jurassic mudrocks, and have thus begun to shed sediments from the more sand rich, pre-Jurassic sequences.

7.3 Marine Sandstones

The following figure 7.5 is an example of an N/G estimate taken from a marine sandstone unit located at Cloughton Wyke. The outcrop shows a sequence from the Scarborough formations Helwath Beck member, which is a shallow marine sequence that overlies the crevasse splay deposits and overbank mudstones/coals of the Gristhorpe member. The Helwath Beck member can be divided into two units (Rawson and Wright 1995); a lower unit composed of dark grey siltstones and very fine, micaceous sandstones, and an upper unit which is made up of sheet-like, resistive, cross-stratified, fine sandstones (2.5 meters). Although these sands are very fine grained, they still maintain relatively good porosities (14-25% see figure 5.6 page 71).

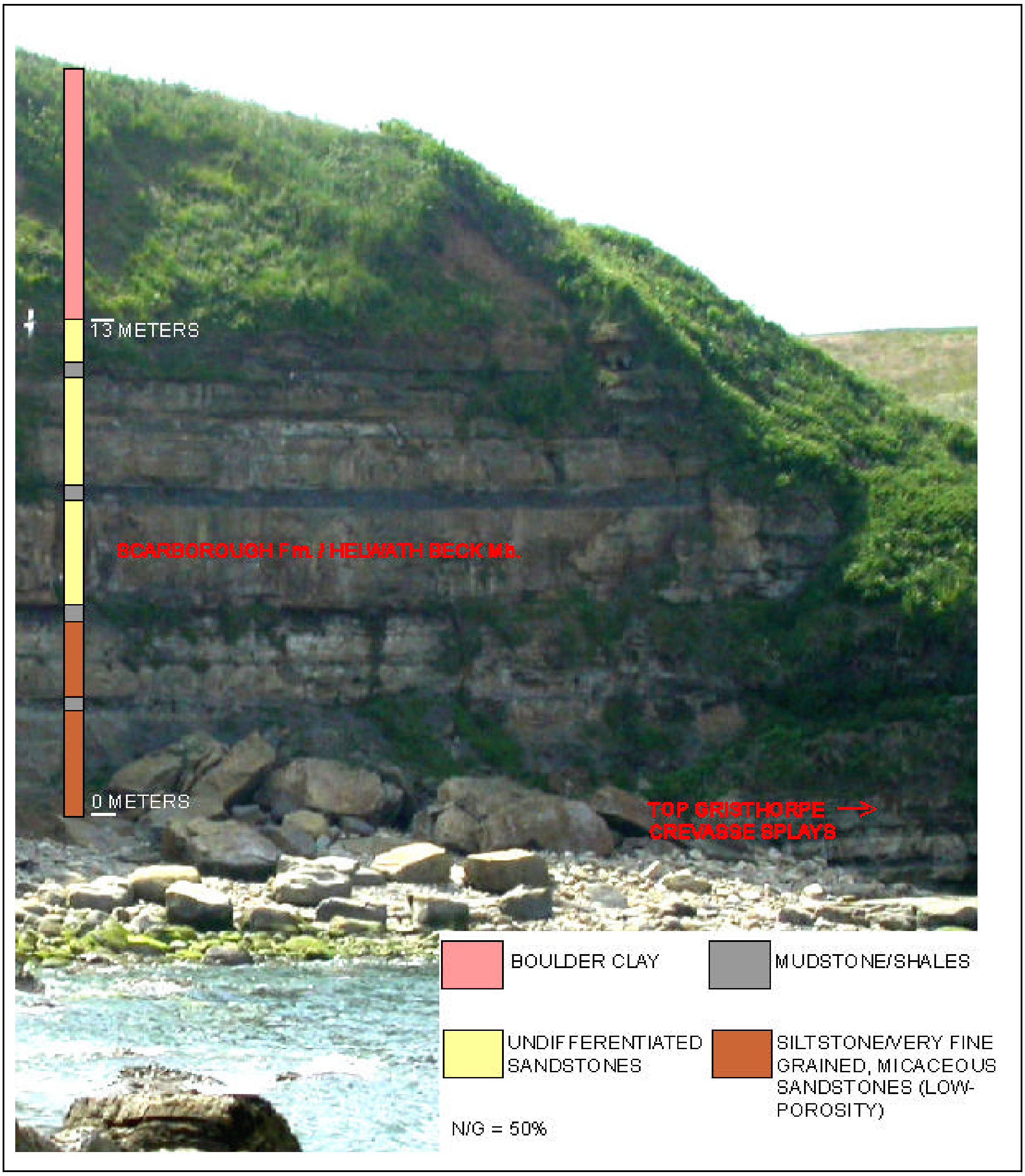


Figure 7.5. Cliff-section at Cloughton Wyke composed of the lower Scarborough marine sands of the Helwath Beck Member. N/G estimate = 50%.

7.3.1 Discussion of Marine Sandstone N/G Estimates

Although the porosity and N/G values are adequate in this example, the overall reservoir potential for this and the other shallow-marine sandstones of the Ravenscar Group is low. The Helwath Beck member is interpreted as a coarsening-upward unit going from silty, shallow-marine-embayment deposits to cross-stratified, barrier shoreface sandstones (Rawson and Wright 1995). Similar to the other marine sands of the Ravenscar Group (Eller Beck and Lebbertson), the Helwath Beck sandstone unit is very thin (2.5 meters). This was due to a depositional setting which was located in an embayment type environment with relatively low wave-energy. This low wave-energy is the main factor in limiting the reservoir potential of the Ravenscar Group marine sandstones. With higher wave-energies, like those found during the deposition of the age-equivalent Brent Group in the northern North Sea, shallow marine sequences can reach greater thickness, have a greater median grain size and tend to be better sorted. In the Brent Group, the shallow marine sandstones of the Rannoch member are composed of a thick, coarsening-upward sequence reaching a maximum of thickness of approximately 60 meters (Morten et. al. 1992). The Ravenscar Group marine sands however, only reach a maximum thickness of a few meters, and therefore do not display good reservoir potential.

[Further comparisons with the Brent Group will be discussed in the following chapter in section 8.4, *Discussion of the Ravenscar Group of Yorkshire as an Onshore Analogue to the Offshore Brent Group*]

Chapter 8 Discussion

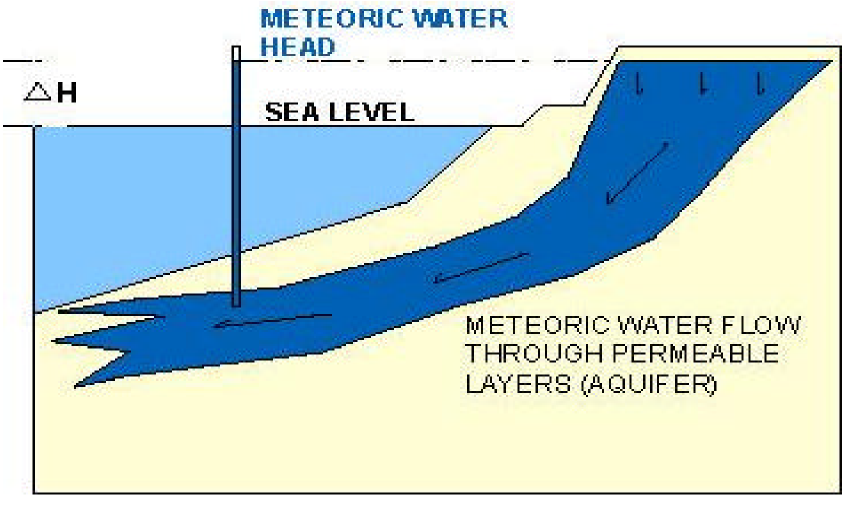
8.1 Meteoric Water Flow and Early Diagenesis of Sandstones

8.1.1 Introduction

It is evident that the channel sandstones of the Ravenscar Group experienced a relatively greater degree of meteoric water flushing than its crevasse splay counterpart. The channel sandstones displayed higher porosity values and a relative greater fraction of authigenic kaolinite, which indicates that the degree of early diagenesis was somewhat controlled by sandstone facies architecture.

Meteoric water flushing plays a very important role in the early diagenesis of sandstones. Its effects can be linked to specific facies, and it can have a very strong influence on burial diagenesis and reduction of porosity (Bjørlykke and Høeg 1997). Meteoric water is rain water which infiltrates into the ground. Due to its distilled and slightly acidic nature, it results in the dissolution of surrounding minerals in an attempt to reach equilibrium. The term flushing is the process which happens due to recharge (rain) and the flow of this water through porous sediments. The ground water table represents the head or potentiometric surface for meteoric water flow. Because the ground water table is normally above seal level, ground water has a potential to flow down through porous sediments possibly far below seal level (Figure 8.1). The depth to which meteoric water will infiltrate down into a basin in determined by the height of the ground water table above sea level, and the density difference between meteoric water and the sea water (Equation 1) (Bjørlykke 2001).

Figure 8.1



$$H = \frac{h\,(p_{fw})}{p_{sw} - p_{fw}}$$

H = depth of meteoric water below sea-level

h = height of groundwater table above sea level

p_{sw} = density of salt water

p_{fw} = density of fresh water

At $p_{fw} = 1.0 g/cm^3$ and $p_{sw} = 1.025 g/cm^3$, H = 40

Equation 1

8.1.2 Leaching of Potassium Feldspars and Precipitation of Kaolinite

Due to the fact that meteoric water is not in equilibrium with the surrounding minerals, the process of dissolution and precipitation takes place. One of the most significant mineral exchanges during this process of early diagenesis is the dissolution of potassium feldspars and the precipitation of kaolinite (Equation 2) (Thyne et. al. 2001).

$$\underset{\text{(K-feldspar)}}{2K\,Al\,Si_3\,O_8} + 2H^+ + 9H_2O \rightarrow \underset{\text{(Kaolinite)}}{Al_2\,Si_2\,O_5\,(OH)_4} + 4H_4\,Si\,O_4 + 2K^+$$

Equation 2

The rate of leaching of potassium feldspar and the precipitation of kaolinite is dependent upon the rate or flux of meteoric water flowing through a giving unit of rock, and the amount of time that unit is exposed to meteoric water flushing. Shallow sediments will undergo the most intense leaching because the meteoric water flux will decrease with depth, and meteoric water becomes less under-saturated with respect to potassium feldspar. Climate (rainfall) and sedimentation rate (rate of subsidence) will also have strong influences on the amount of leaching that takes place. When sedimentation rate is low, or the climate is wet (high flux), the amount of leaching will be greater due to the fact that the sediments are exposed to either a longer period or a greater amount of meteoric water flushing.

As seen in the above equation (Equation 2), this process is dependent upon a low K^+/H^+ ratio. This means that the reaction requires flow and the removal of stripped potassium ions, and a supply of fresh water (H^+) for the process to continue. Meteoric water tends to be slightly acidic which helps this process along, but a low pH is not required. Even if the meteoric water is neutralized or slightly basic, the process will continue as long as the K^+/H^+ is correspondingly lower (Bjørlykke 1993).

The precipitation of kaolinite is a function of a sediments mineralogical composition, ie: amount of mica and potassium feldspar, and the processes that it was subjected to during deposition and burial. The amount of precipitated authigenic kaolinite can therefore provide important information about a given unit of sediments. Information regarding provenance, facies, sedimentation/subsidence rates and paleo-climate can be interpreted from the degree of kaolinite precipitation.

8.2 Discussion of Results

The channel sandstone samples examined under the SEM were on average the coarsest and most porous (avg. 18%) of the three investigated facies. This was expected due to the higher energy depositional environment. All of the channel sandstone samples showed a greater relative kaolinite fraction than samples from the crevasse splay sandstones. The potassium feldspar content was not quantifiable using the SEM area measurement procedure due to its similar contrast energy as quartz. Despite this, conclusive results were achieved by the consistent recognition of greater kaolinite fraction within the channel sandstones. Average kaolinite content based on backscatter SEM area measurements for channel sandstones was 17.5% and the average for the crevasse splay sands was 9.7%. XRD was used to measure the relative amounts of potassium feldspar and kaolinite. XRD results found no potassium feldspar in the channel sandstone samples; where as all of the crevasse splay samples had significant amounts. Both SEM and XRD results were consistent with one another, and indicated that the channel sands experienced a higher degree of meteoric water flushing and consequently a greater degree of potassium-feldspar leaching and precipitation of kaolinite. The more porous channel sandstones acted as fluid-flow conduits and due to a greater volume of meteoric water flushing, all of the available potassium-feldspars were dissolved and re-precipitated as kaolinite. On the contrary, the crevasse splay sandstones, which are finer grained and commonly pinch-out forming fluid-flow ‘dead-ends’, did not experience the same flux as the channel sandstones., thus resulting in less leaching of potassium feldspars and therefore less precipitation of authigenic kaolinite.

The amount of kaolinite precipitated is very dependent upon the flux. This is the amount of meteoric water which passes through a given volume of rock in a certain period of time (Equation 3). In a meteoric water flow setting, the limiting factor for flux and therefore the degree of meteoric water flushing and leaching is the rate of recharge, i.e. rainfall. This is in contrast to systems without meteoric water influx where the flux is limited by the rate of compaction and expulsion of fluids from underlying sediments (Bjørlykke 1999).

$$\textbf{Flux} = \frac{\textbf{Permeability} \cdot \textbf{Pressure Gradient}}{\textbf{Viscosity}}$$

Flux = cm3/cm2/second

Equation 3

In general, channel sandstones are subject to a relatively higher meteoric water flux, when compared to crevasse spay sandstones. This is for a variety of reasons: They tend to be coarser and porous enough to maintain adequate permeability; they are directly associated with meteoric water; and they can provide a continuous conduit to shallow marine sands for further flow into a basin. Some channel morphologies, such as those found in the lower Ravenscar Group, form isolated sand bodies. These may not be so conducive for meteoric water flow, but as seen in the results of this study, they still offered a much better conduit for fluid-flow than the crevasse splay sandstones. Unless a crevasse splay is incised by a channel, it normally thins and eventually pinches out with distance from the feeder channel. In addition, the median grain size of crevasse splay sandstones tend to be fine grained and decrease in caliber with distance from the main channels, which further limits their potential for fluid-flow. Grain size comparison can be seen in Figure 8.3 (channel) and 8.4 (crevasse splay).

Due to their tendency to pinch out, and their fine grained make-up, crevasse splay sands do not generally experience the same degree of meteoric water flushing, i.e. precipitation of kaolinite, that channel sands do. In order for meteoric water flow to occur, it must have a porous and semi-continuous pathway. Crevasse splay sands generally have lower permeability and do not form continuous pathways for flow. They tend to thin and pinch out into a matrix of overbank fines and form somewhat of a 'dead-end' for meteoric water flow. As the SEM and XRD results show, the crevasse splay sandstones precipitated less kaolinite and had remaining potassium-feldspar which demonstrates that they were subject to less meteoric water flow than the channel sandstones.

Although channel sands do sometimes form isolated, abandoned channel bodies, they generally make much better conduits for fluid flow. Permeability which is one of the main factors determining flux (Equation 3) is generally relatively higher in fluvial channel sandstones. SEM and XRD results supported this concept with all of the channel sandstone samples showing a greater fraction of kaolinite and complete depletion of potassium-feldspar.

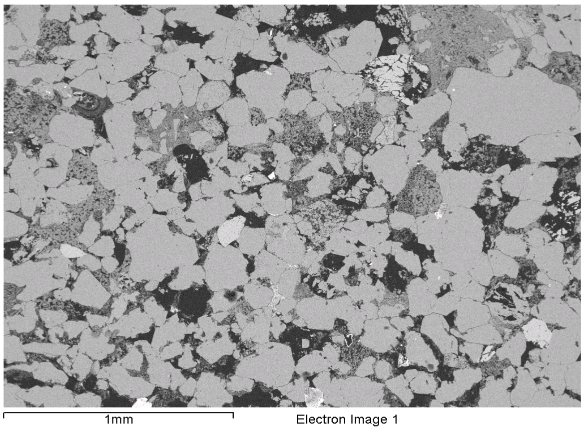


Figure 8.2. SEM image of a channel sandstone displaying a much coarser and more porous nature than the below crevasse splay sample.

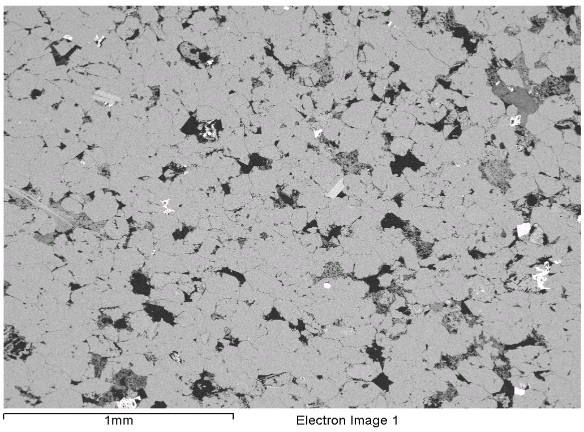


Figure 8.3.SEM image of a crevasse splay sample displaying a finer grained and less porous composition than the above channel sandstone sample.

8.2.1 Reservoir Quality Implications

The channel sandstones of the Ravenscar Group all had significant amounts of kaolinite (17.5%), and little or no remaining potassium-feldspars. The crevasse splay sandstones had relative lower amounts of kaolinite with some remaining potassium-feldspar. These are important factors when considering reservoir potential.

The amount of kaolinite within a sandstone unit can have significant implications on reservoir quality. Although the dissolution of potassium feldspar can initially create secondary porosity, in most cases an equal volume of pore space will be lost due to the precipitation of kaolinite. Authigenic kaolinite tends to precipitate within the pore space (Figure 8.2). This can result in a reduction in permeability, as well as a decrease in median pore size. The smaller pores created by the precipitation of kaolinite within the pore space can lead to higher water saturation if the capillary entry pressure becomes too high for oil to enter those small pores.

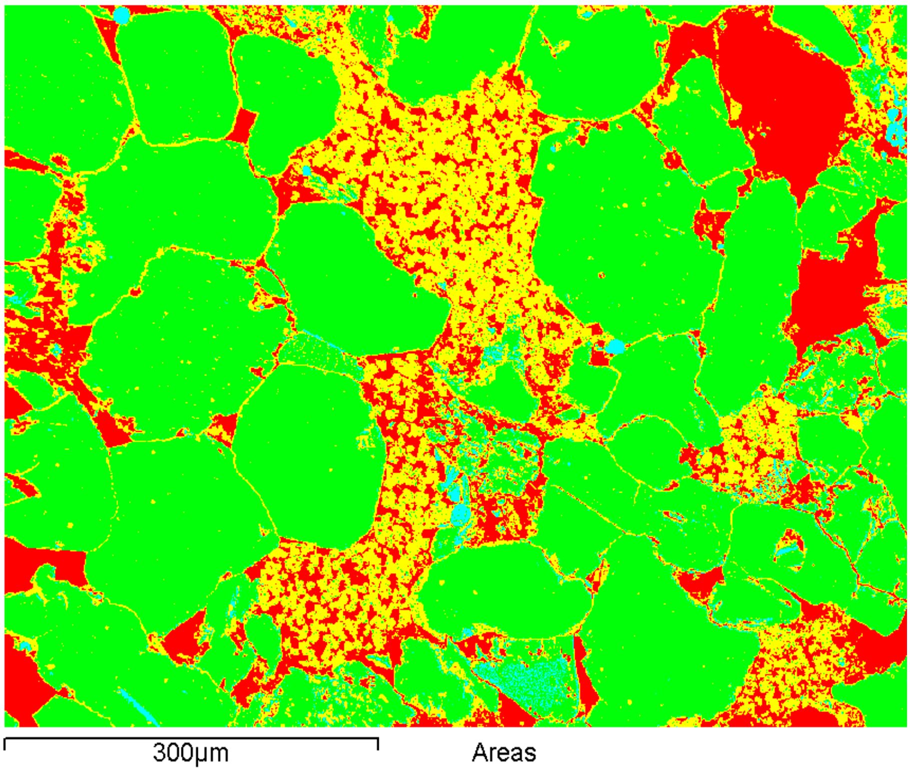


Figure 8.4. SEM backscatter image of a channel sandstone with contrast intensities: Red = porosity, Yellow = pore-filling, authigenic kaolinite, Green = detrital grains and Blue = heavier minerals (Ti). Note reduction in mean pore size and increase in micro-porosity

Although the above mentioned effects can result from high amounts of precipitated kaolinite, it is usually not in itself detrimental to a reservoir. But at greater depths/temperature, and if there is a source of potassium available, kaolinite will be replaced by the more stable illite (equation 4) (Bjørlykke 1999). The mineral illite is, in itself, very detrimental to reservoir quality, i.e. permeability. The fibrous nature of illite can drastically reduce permeability by clogging the flow of oil through pores. The fact that the channel sandstones of the Ravenscar Group are completely depleted of potassium-feldspar is important because with out an available source of potassium, illite will not form, and therefore porosity and permeability may be better preserved at greater depths. In addition, the fact that crevasse splay sands had remaining potassium-feldspar and kaolinite, but no illite, indicates that these units did not reach burial depths/temperatures equal to 130 degrees Celsius. Both of the above noted facts provide vital information which can be used to predict reservoir quality of related facies at greater depths/temperatures.

The processes involved in the precipitation kaolinite, and the clues that it can provide are therefore very important in study of sandstones and reservoir geology. It has been one of the main goals of this paper, to use relative kaolinite and potassium feldspar amounts as an indication of degree of diagenesis, meteoric water flushing, and consequent reservoir implications.

$$\mathbf{K\,Al\,Si_3\,O_8 + Al_2\,Si_2\,O_5\,(OH)_4 \rightarrow K\,Al_3\,Si_3\,O_{10}\,(OH)_2 + Si\,O_2 + 2H_2O}$$

K-Feldspar + Kaolinite = Illite + Quartz

@130°C

Equation 4

8.3 Comparison with Previous Study

A comprehensive petrographic and diagenesis study of Yorkshire's Ravenscar Group sandstones was completed by J.D. Kantorowicz, and published in 1985: '*The petrology and diagenesis of Middle Jurassic clastic sediments, Ravenscar Group, Yorkshire*'. The goal of Kantorowicz's study was to "identify and to assess the significance of possible controls on diagenesis". Three hundred samples were collected and detailed petrography and diagenetic interpretation was completed. The following is a summary of the Kantorowicz's study, of which, applicable parts will be discussed and contrasted.

8.3.1 Summary of Kantorowicz, 1985

Kantorowicz identifies three regimes where diagenesis took place; eogenesis – within the depositional groundwater; mesogenesis – during burial; and telogenesis – during uplift and erosion. He identifies and compares the diagenetic effects within the three dominant facies present within the non-marine Ravenscar Group members; channel sandstones, floodplain facies sandstones (crevasse splay), and floodplain facies mudrocks.

Channel Sandstones:

Petrographic studies for channel sandstones found them to be generally medium to fine grained, supermature or mature quartz arenites and subarkoses. Authigenic minerals comprise 10-30%, and the most significant were quartz overgrowth, siderite and kaolinite (dickite). Porosity averaged 15% with highs around 30%. Samples with a higher percentage of authigenic minerals, i.e. kaolinite had a greater percentage of their porosity represented by micro-porosity. Chlorite is observed, but is mutually exclusive with kaolinite, and illite occurs in association with detrital micas.

Floodplain Facies Sandstones:

The floodplain facies sandstone samples examined by Kantorowicz ranged from medium grained sandstones to highly micaceous siltstones. The majority were texturally mature, subarkoses with occasional quartz arenites. The floodplain facies sandstones generally had a lower porosity than that of the channel sandstones with an average of 5% and values that ranged from 1-14%. Authigenic mineral composition ranged from 10-50%, and was predominantly quartz, kaolinite and siderite.

Diagenesis:

Kantorowicz interpreted that there was no significant difference in diagenesis for the different facies, apart from the quantity of authigenic minerals present. The first mineral reactions to occur after deposition were interpreted by Kantorowicz as the partial alteration/dissolution of muscovite and potassium feldspar and the precipitation of kaolinite, chlorite and quartz overgrowths. This was attributed to the mildly acidic conditions caused by aerobic bacterial degradation of organic matter and release of bi-carbonate into solution which further lowered the pH. Alumina and silica released as a result of this low pH caused the pore water to become saturated with respect to quartz and kaolinite. In other parts of floodplain where anaerobic conditions existed, anaerobic bacterial activity began resulting in the reduction of sulphates and then ferrous iron. These conditions favored the precipitation of chlorite rather than kaolinite.

8.3.2 Comparison of Results

The results of my study showed similarities to those of Kantorowicz. Detailed petrographic analysis was beyond the scope of this study, but some general petrographic observations were made, along with detailed porosity and authigenic clay fraction measurements: Channel sandstones were comprised of fine to medium grained, quartz dominant sandstone with an average porosity of 17.5% and an average authigenic clay fraction of 17.5%. Crevasse splay sandstones were relatively finer grained with a higher fraction of micas and had an average porosity similar to those of the channel sands at 16.9% and an average authigenic clay fraction of 9.7%. I observed a relative greater porosity and higher kaolinite fraction within the channel sandstones compared to those of the crevasse splay sandstones. The above results were consistent with those of Kantorowicz, and indicate some consistency between these two independent studies.

8.3.3 Discussion of Kantorowicz, 1985

The results of these two independent studies have many parallels, but the diagenetic interpretations differ substantially.

As noted in the above summary of Kantorowicz's results, he suggests an early phase of quartz precipitation due to low pH and subsequent silica saturation. I have interpreted the formation of authigenic quartz as a late diagenetic reaction as a product of increased temperatures during progressive burial. It is now accepted that the precipitation of authigenic quartz probably does not occur at low temperatures (<70° Celsius), due to the low activation energy of quartz (Walderhaug 1994). The formation of secondary quartz is essentially controlled by temperature and precipitation. Due to the slow kinetics of quartz at low temperatures, it does not readily precipitate, despite silica saturation. If there is no precipitation, then there is no drive for dissolution. In his discussion, he does note that: *"Pore-water chemistry is often proposed as a fundamental diagenetic control. However, the amount of cement which can be deposited from a single pore volume is negligible. In order to precipitate quartz and siderite cements many pore volumes must have passed |through the sediments…It was the interaction of this water with the sedimentary assemblage which most influenced diagenesis"* (Kantorowicz 1985, page 846). This is a strong statement by Kantorowicz, but it lacks to mention the importance of temperature. Kantorowicz's interpretation of early authigenic quartz formation does not fit the current understanding of authigenic quartz formation, and in addition, he does not stress the importance of meteoric water flow as the main factor in the dissolution of micas/potassium feldspars and precipitation of kaolinite. Meteoric water flow and the resulting effects of dissolution and precipitation have since become one of the most significant factors in the early diagenesis of sandstones. I believe that this early interaction with meteoric water was the primary drive for early burial diagenesis and led to the first major mineral transition.

The study by Kantorowicz was broad and attempted to cover all aspects of diagenesis. Unlike Kantorowicz, I focused on the effects of meteoric water flushing and the different degrees of diagenesis that it resulted in. Although a different scope and focus, the analytical results of Kantorowicz and the present paper are quite parallel. Porosity values, authigenic mineral volumes, and textural data corresponded. Consistent with Kantorowicz's interpretation, my data supported a lower amount of authigenic minerals and a lower porosity within the floodplain facies sandstones; and corresponding higher values for the channel sandstone facies. I have interpreted this larger amount of authigenic mineral precipitation within the channel sandstones to be a result of a relative greater amount of meteoric water flushing compared to the sandstones from crevasse splays. Kantorowicz does not stress this as the dominant factor in early (shallow) diagenesis but rather the lowering of pH due to aerobic bacterial degradation and release of bi-carbonate. This was undoubtedly a major factor in the degree and type of early diagenesis, but the without maintaining a low K^+/H^+ ratio the process of dissolution and precipitation will not continue (as discussed in previous section 8.1.2).

Although Kantorowicz does not stress meteoric water as the main factor in early diagenesis, he does recognize that the sand body geometry had an important control on authigenic mineral distribution:

"Sandbody geometry and in particular the alluvial architecture of the original sediments were also important controls on the distribution of authigenic modifications in the subsurface. Large and connected channels-facies sandstones, as well as nearby flood-plain-facies deposits, are now relatively porous, but also contain significant quantities of dickite. Conversely, smaller, more isolated sand bodies, and especially thin flood-plain-facies sandstones are often tightly cemented, or less porous, and contain less dickite. It appears, therefore, that the larger sand bodies were conduits for pore-fluid migration in the subsurface, whilst the smaller sands remained unaffected by the activities of these solutions." (Kantorowics 1985, page 850).

This statement shows an agreement between these two independent studies. It was a goal of my study to prove that the larger, more continuous sand bodies of the channel sandstone facies experienced a relative greater amount of meteoric water flushing compared to the smaller crevasse splay facies sandstones. My data supported this theory and was consistent with the above statement by Kantorowicz: The large channel-facies sandstones showed a greater porosity and an increased amount of kaolinite; where as the crevasse splay sandstones had lower porosities and a relative less amounts of kaolinite. Although the scope, focus and interpretation of these two studies differ, the findings related to the meteoric water flow and its diagenetic effects within the different facies, support and agree with one another.

8.4 Discussion of the Ravenscar Group of Yorkshire as an Onshore Analogue to the Offshore Brent Group

As mentioned previously, one of the primary attractions to the Ravenscar Group of Yorkshire is its contemporaneous nature to the offshore North Sea Brent Group. These time-equivalent sequences were deposited in a fluvio-deltaic setting and were the product of similar controls: Thermal doming and uplift of the Mid-North Sea High (source area), tectonic extension and related thermal subsidence with resulting sea level fluctuations, variations in sedimentation rate and sediment consolidation (Morten et. al. 1992). In addition, the climate and sedimentary processes were similar, and the resulting complex successions of marine and non-marine sediments are comparable. These similarities have frequently led to the use of the Middle Jurassic Ravenscar Group of the Cleveland Basin as an illustrative analogue for the Brent Group, but it is important to remember that although these similarities do exist, they are only broadly related, and there are definite limitations. It is beyond the scope of this paper to discuss the Brent Group in detail but some general points can be made.

8.4.1 Introduction to the Brent Group of the N. North Sea

The Brent Group is economically one of the most important successions in the North Sea. Most of Britain's oil reserves, as well as Norwegian North Sea reserves, are found in these Middle Jurassic sandstones (or equivalent). It is a clastic unit of Late Toarcian to Bathonian age, and is found in the East Shetland Basin, Viking Graben and Bergen High areas of the northern North Sea (Morten et. al. 1992). The Brent Group is roughly 300 meters thick within the East Shetland Basin and is comprised of five formations, which are consequently named after the five letters in BRENT. In ascending stratigraphic order they are: Broom, Rannoch, Etive, Ness, and Tarbert. The group is described as a regressive – transgressive wedge (Brown et. al 1987). In general, the Broom, Rannoch, Etive and Lower Ness comprises the northward prograding regressive part of the succession, where as the succeeding Upper Ness and Tarbert formations were deposited during the retreat of the system as a result in sea level rise (Morten et. al. 1992). This deltaic, or coastal complex system, prograded northwards into an open sea and was subject to high-energy waves. Fluctuations in sea level produced a complex succession of marine and non-marine sequences similar to those from the Ravenscar group.

8.4.2 Discussion of Analogue Application

Although these two time-equivalent systems are very similar there are limitations in using the Ravenscar Group as an analogue for the Brent Group. One key difference was the depositional setting: The Brent Group was a large delta or coastal complex system which prograded northwards into an open sea with relative high wave-energy. Strong longshore currents caused by this high wave-energy approached the mainland from the north and redistributed sediments. On the contrary, the Cleveland Basin was located in a small embayment, delineated to the north by the Mid-North Sea High, the east by the Pennine High, and to the south by the Market Weighton Block (Figures 8.5 and 8.6). This embayment type setting was protected from the open sea and consequently experienced lower wave-energies. Essentially, it can be said that the Brent Group was deposited in a wave-dominated delta setting, whereas the Ravenscar Group was deposited in a fluvial or possibly tidal dominated delta setting. In addition, the scale of these two systems must be considered. The Brent Group was deposited in a much larger setting with a greater drainage area and input of sediments. These variations in depositional settings and scale, combined with the interplay of such factors as sedimentation rate, compaction, and local tectonic activity have lead to significant differences in degree of marine influence and sandstone body architecture and make it very difficult to accurately compare these two groups.

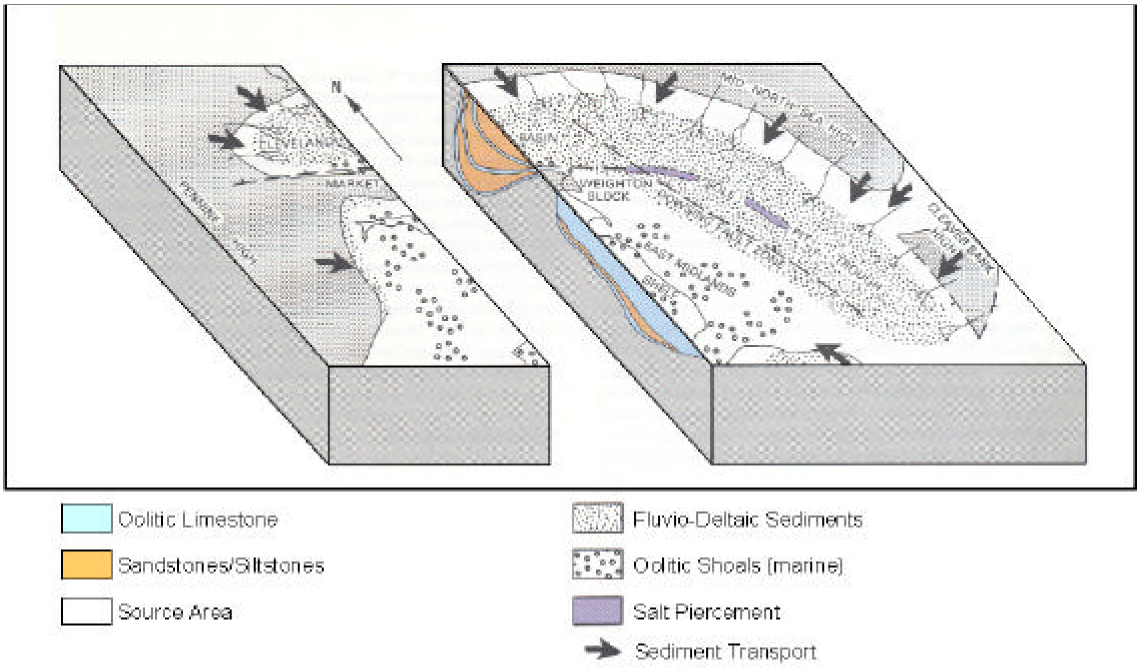


Figure 8.5. Depositional model for the Middle Jurassic Cleveland Basin (Cameron et. al. 1992).

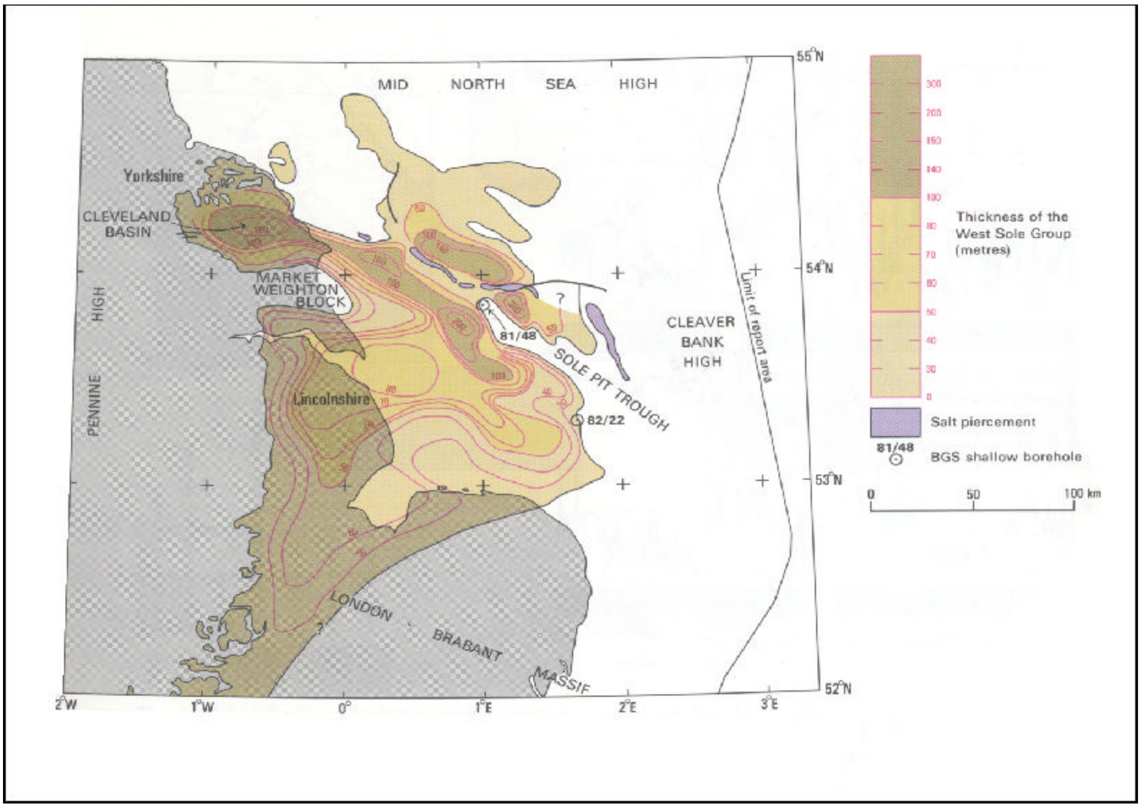


Figure 8.6. Isopach map showing distribution and thickness of Middle Jurassic rock within a delineated Cleveland Basin (Cameron et. al. 1992).

Reservoir Quality Implications:

The fact that the Cleveland Basin experienced less wave energy, compared to the Brent Group, is significant when discussing reservoir potential. The low wave energy of the Cleveland Basin led to the deposition of only thin marine sandstone sequences (the Eller Beck formation, 1-3 meters sandstone, and the Lebbertson member, 2-5 meters sandstone). In contrary, the higher wave-energy depositional setting of the Brent Group produced marine sandstones of considerable thickness (Rannoch ma ximum thickness of 60 meters). The embayment type setting of the Cleveland Basin had a relatively shallow fair weather wave base (FWWB) and a coinciding low storm weather wave base (SWWB). This limited the distribution of sand, and led to the deposition of only thin marine sand sequences. This leaves the fluvial sequences of the Saltwick formation, the Cloughton formation and the Scalby formation for consideration as potential reservoir rocks. As observed in Yorkshire outcrops, and displayed in the net to gross estimates of this study, these fluvial sequences appear to be dominated by overbank fines, and have a very low overall sand to shale ratio.

Although the Ness Formation of the Brent Group is considered to have the poorest reservoir quality of the group, when it is compared to the fluvial sands of the Ravenscar Group, it displays much better sand to shale ratios (Figure 8.7). It is possible that these low sand to shale ratios within the Ravenscar Group can be attributed to the fact that the Lower Jurassic sequence (Liass) in and around the Cleveland Basin was considerably thicker and more mudstone rich than that of the northern North Sea area. Uplift during Middle Jurassic led to the erosion and re-deposition of these mudstones coincidently with the deposition of the fluvial sequences, which may have led to their mudstone rich nature. This can be demonstrated by comparing the two figures below, 8.7 and 8.8: Figure 8.7 is a log through the Ness formation, and although it indicates a substantial amount of overbank fines, the overall sand to shale ratio is much better than that observed in Figure 8.8.

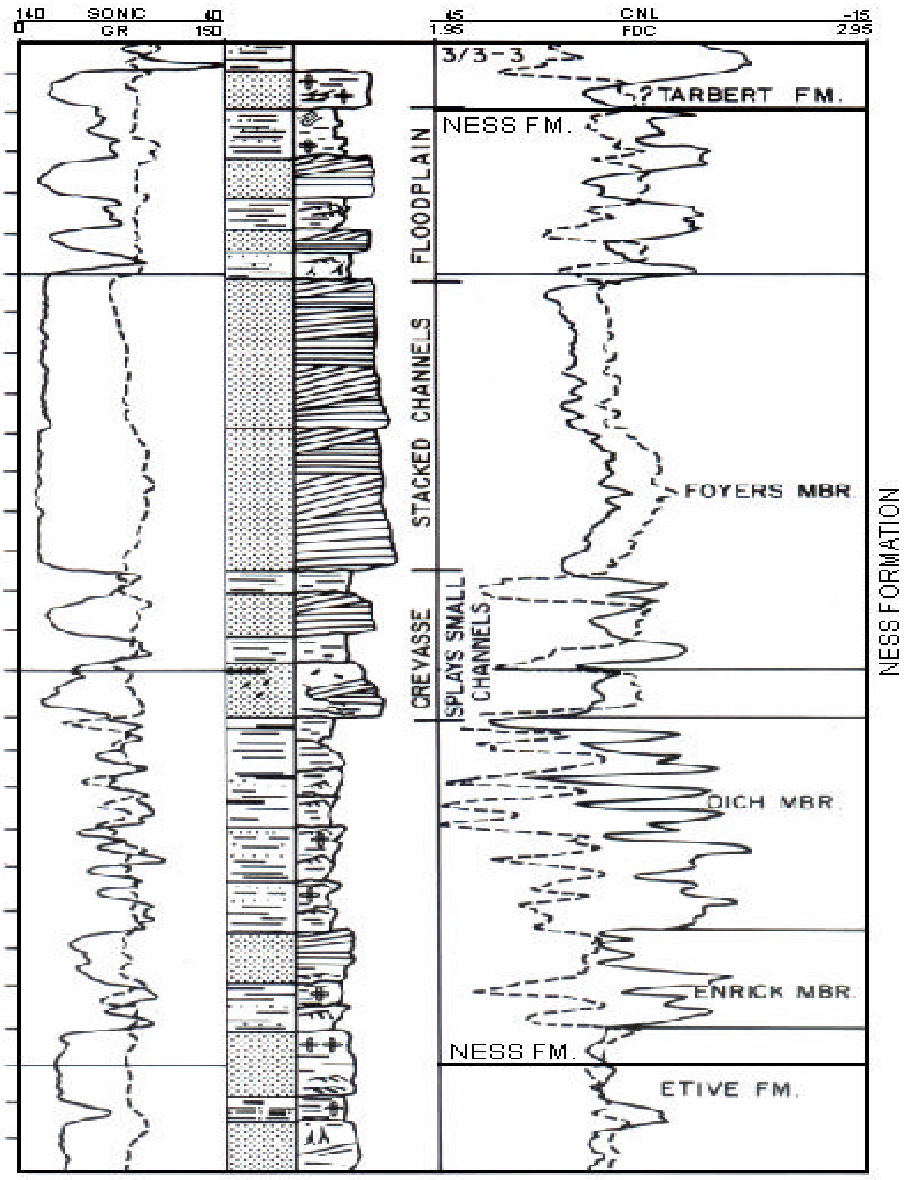


Figure 8.7. Log from the Ness formation of the Brent Group showing inter-bedding of sands and over-bank fines. Estimated N/G of 60% (modified from Morten et. al. 1992).

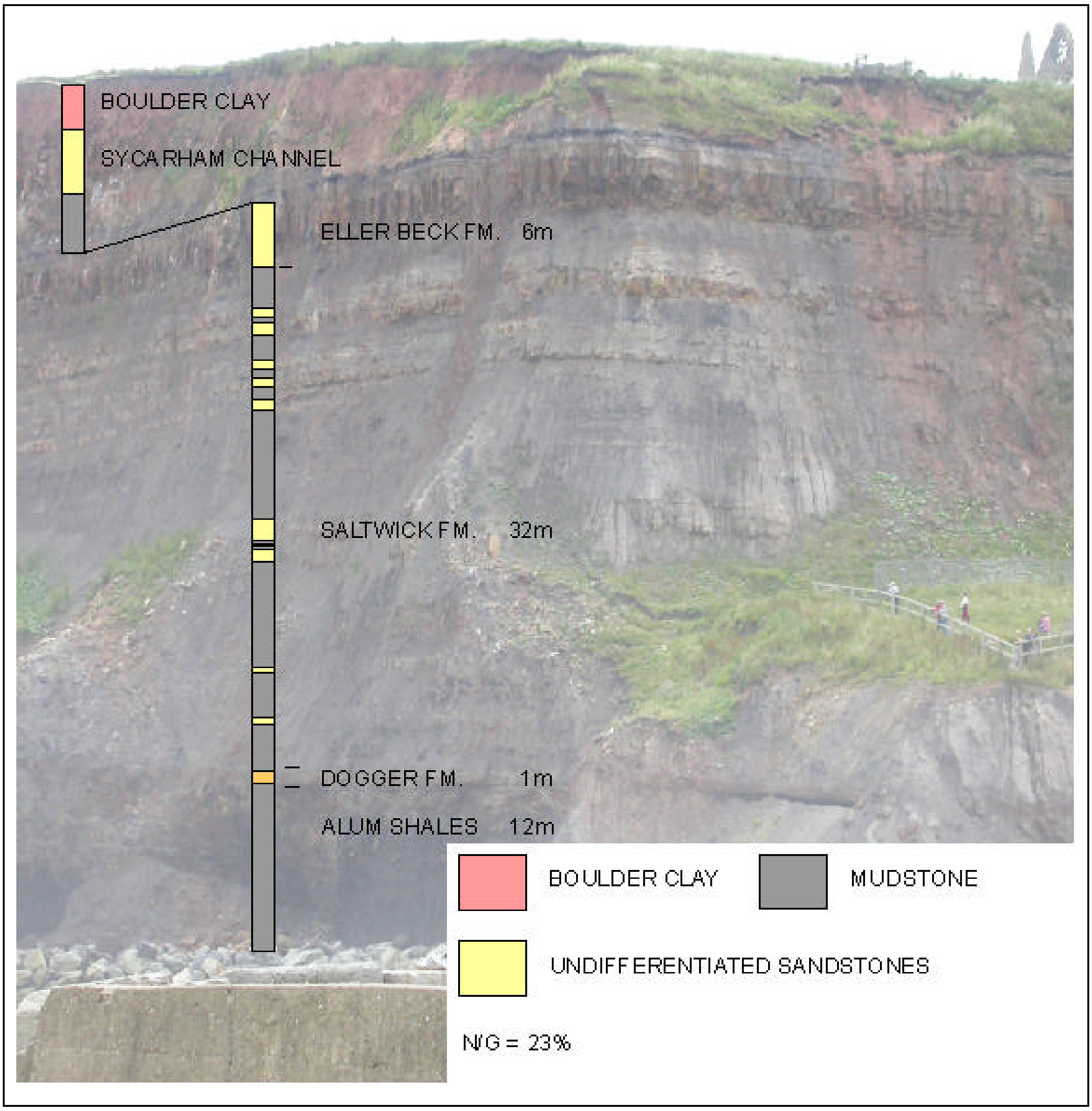


Figure 8.8. N/G estimate from a cliff outcrop located just east of Whitby Bay and the Whitby fault. The sequence is dominated by overbank fines mudstones and only minor amounts of crevasse splay sands. Estimated N/G is 23%.

Conclusion:

Although the above inconsistencies exist, and even though the analogue is by no means perfect, the similarities in climate and depositional processes still provide for an attractive model for comparison and illustration of variations in the offshore Brent Group. But it is important to take into account, that although they are very similar, the differences that do exist can have dramatic effects on depositional patterns and limit the accuracy of such analogues.

Chapter 9 Summary and Conclusions

9.1 Summary and Conclusions

The main goal of this study was to examine and evaluate the reservoir qualities of the Middle Jurassic sandstones of Yorkshire. General petrographic evaluation was completed, and porosity and authigenic clay fractions were semi-quantified using SEM and XRD analysis. Field work was completed, and sandstone body distribution and characteristics were identified.

It is readily observed in Yorkshire that the channel sands of the Ravenscar Group are sparsely distributed and commonly occur isolated within a matrix of overbank mudstones. Of course there are exceptions to this, such as the Whitby west example and some of the Scalby formation, but in general, based on distribution and stacking patterns, the overall reservoir quality of this sequence is poor. Without some type of control on the distribution of these channels, like that exerted by the paleo-Whitby fault, the channels are too sporadically distributed to make a good reservoir. There are common laterally extensive crevasse splay sandstones, but their fine-grained nature and tendency to pinch-out laterally makes them overall poor reservoirs. As for the marine sandstones of the Ravenscar Group, they are simply too thin to be considered to have any reservoir potential.

An attempt was made to identify the degree and main control of early diagenesis. It was evident that the more porous, channel sandstone units provided a better pathway for fluid-flow and were thus subject to a greater degree of meteoric water flushing. The channels sandstones were completely depleted of potassium-feldspar, and had relatively high amounts of kaolinite. It can therefore be assumed that related sandstones at greater depths and temperature would not form illite due to this lack of potassium. The fact that illite cannot form, may enable these deeper sandstones to preserve adequate porosities and permeability for production. Whereas in places where there was an available potassium source, the combination of kaolinite-illite transformation and quartz cementation would have a greater chance of destroying any remaining porosity.

In contrast, the crevasse splay sandstone had remaining potassium-feldspar, and overall lower kaolinite fractions. Due to their tendency to pinch-out into a matrix of overbank fines, crevasse splay sandstones do not offer an ideal pathway for fluid-flow, but rather a 'dead-end', thus experiencing a lesser degree of meteoric water flushing and leaching of potassium feldspar. It is also evident from the occurrence of both kaolinite and potassium-feldspar that these units were not buried deep enough (temperature of 130 degrees Celsius) to undergo illitization. Due to substantial quartz overgrowths, we can assume that these units probably experienced a minimum temperature of approximately 80 degrees Celsius (Walderhaug 1994) but due to the lack of illite (or presence of kaolinite and potassium-feldspar), we can conclude that it had not been exposed to temperatures equal to or greater than 130 degrees Celsius, for any significant period of time.

It is evident by these results that facies and sandstone body architecture play a significant role in fluid-flow properties and early diagenesis, which in turn can have dramatic effects on reservoir quality.

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Appendix A

Appendix B