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ABSTRACT

The Sedimentology and Stratigraphy
of the Sherwood Sandstone Group
in NW England

Neil Sutherland Meadows

The existing stratigraphic nomenclature applied to the Early Triassic Sherwood Sandstone Group in NW England has resulted from more than 150 years of geological investigation but is characterised by a stratigraphic system that fails to allow for variations in lithology and sedimentary facies. The main objective of this thesis has been to erect an alternative lithostratigraphy using an improved understanding of continental depositional systems, a consistent facies based description of the rocks and analysis of their detrital composition.

The sedimentology of the Sherwood Sandstone Group is described in terms of four depositional environments comprising fluvial channels, sandflats including aeolian dunes, floodplains including playa lakes and alluvial fans. The mineralogy of the sandstones reveals variations in feldspars, rock fragments and heavy minerals that have stratigraphic implications suggested to be related to subtle variations in their provenance. The detrital chemistry of the sandstones in four offshore wells has been determined using ICP-AES and ICP-MS analyses and this confirms stratigraphically significant variations across all four wells that does not relate to either sedimentary facies or to the existing stratigraphy.

A revised well correlation based on the mineralogical and chemical data confirms previously suggested but unproven diachroneity at the top of the Sherwood Sandstone Group and reveals incised valleys filled by stacked fluvial channel sandstones through the upper parts of the group. A combination of well sections suggests these were cut by a fluvial system flowing NW from the Cheshire Basin into the East Irish Sea Basin and then W towards the Peel and Kish Bank Basins. This contrasts with the N flowing system responsible for the lower parts of the group which exited the East Irish Sea Basin towards Solway.

Four distinct stratal geometries are apparent within the Sherwood Sandstone Group. An uppermost marine-influenced succession exhibiting characteristics that accord with models of retrogradational parasequences. A mid to upper succession characterised by incised valleys cut into sandflat facies that accords with models of climatically mediated alternations between aggradation and degradation in fluvial systems and is supported by climatic inferences determined from sandflat facies. A lower succession dominated by stacked fluvial channel sandstones with little or no preservation of non-channelised facies but within which laterally extensive surfaces bound packages of highly heterogeneous fluvial channel fills that are suggested to represent a tectonic control on the creation of accommodation space. A basal succession where sandstones are interbedded with lacustrine facies in a manner that accords with models of progradational parasequence sets.

No single published model of continental sequence stratigraphy accounts for or predicts the variability exhibited by the Sherwood Sandstone Group as most tend to concentrate on a specific variable to the exclusion of others. A simple model is proposed that allows the relationship between sediment flux and the rate of creation of accommodation space to be visualised with respect to the interplay between climate, tectonics and eustasy. This views depositional basins as under-filled, balanced or over-filled with subtle changes in the relationships having profound effects on the resultant stratal architecture

THE SEDIMENTOLOGY AND STRATIGRAPHY OF THE EARLY TRIASSIC SHERWOOD SANDSTONE GROUP IN THE EAST IRISH SEA AND CHESHIRE BASINS OF NW ENGLAND

Ph.D.

NEIL SUTHERLAND MEADOWS

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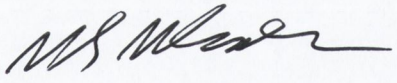

N S Meadows

SUMMARY

The existing stratigraphic nomenclature applied to the Early Triassic Sherwood Sandstone Group in NW England has resulted from more than 150 years of geological investigation. The cumulative consequence of differing perceived stratigraphic requirements, or attempts to solve specific stratigraphic problems, has resulted over time in an inconsistent hierarchy of names and a stratigraphic system that fails to allow for variations in lithology and sedimentary facies. The main objective of this thesis has been to erect an alternative lithostratigraphy based upon an improved understanding of continental depositional systems, a consistent facies based description of the rocks and analysis, both mineralogical and chemical, of their detrital composition.

The sedimentology of the Sherwood Sandstone Group is described in terms of four depositional environments comprising fluvial channels, sandflats including aeolian dunes, floodplains including playa lakes and alluvial fans. Each of these associations is subdivided into distinct facies, related to changing flow conditions in the case of fluvial channel fills, to variably wet to dry conditions controlled by the relationship between the palaeo-surface and the water table in the case of sandflats and aeolian facies and to a combination of lake development and incipient pedogenesis in the case of floodplains. Alluvial fan facies are only positively identified from one locality in the extreme south of the Cheshire Basin.

The mineralogy of the sandstones is dominated by quartz but with significant and variable percentages of K-feldspar, plagioclase and rock fragments including compound quartz, feldspar and mica grains that exhibit either a granitic fabric or a variably low to high grade metamorphic fabric. The proportion of feldspars in the sandstones, of granitic compared to metamorphic rock fragments and of specific heavy minerals varies systematically through the Sherwood Sandstone Group in a manner that has stratigraphic implications suggested to be related to subtle variations in their provenance.

The detrital chemistry of the sandstones in four offshore wells has been determined using ICP-AES and ICP-MS analyses. Specific oxides and trace elements in the dataset closely match the detrital mineralogy and confirm stratigraphically significant variations in the

feldspars and in heavy minerals. The vertical distribution of the changes is consistent across all four wells but does not relate to either sedimentary facies or to the existing stratigraphy.

A revised well correlation based on the mineralogical and chemical data confirms previously suggested but unproven diachroneity at the top of the Sherwood Sandstone Group and also reveals the presence of incised valleys filled by stacked amalgamated fluvial channel sandstones throughout the upper parts of the group. A combination of well sections suggests these were cut by a fluvial system flowing NW from the Cheshire Basin into the East Irish Sea Basin and then W towards the Peel and Kish Bank Basins. This contrasts with the N flowing system responsible for the lower parts of the group which exited the East Irish Sea Basin towards Solway.

Four distinct stratal geometries are apparent within the Sherwood Sandstone Group. An uppermost marine-influenced succession exhibiting characteristics that accord with models of retrogradational parasequences. A mid to upper succession characterised by incised valleys cut into sandflat and aeolian facies that accords with models of climatically mediated alternations between aggradation and degradation in fluvial systems and is supported by climatic inferences determined from variations in sandflat facies. A lower succession dominated by vertically stacked fluvial channel sandstones with little or no preservation of non-channelised facies but within which laterally extensive surfaces bound packages of highly heterogeneous fluvial channel fills that are suggested to represent a tectonic control on the creation of accommodation space. A basal succession where sandstones are interbedded with lacustrine facies in a manner that accords with models of progradational parasequence sets.

No single published model of continental sequence stratigraphy accounts for or predicts the variability exhibited by the Sherwood Sandstone Group as most tend to concentrate on a specific variable to the exclusion of others. A simple model is proposed that allows the relationship between sediment flux and the rate of creation of accommodation space to be visualised with respect to the interplay between climate, tectonics and eustasy. This views depositional basins as under-filled, balanced or over-filled with subtle changes in the relationships having profound effects on the resultant stratal architecture.

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110/8a-5

110/11-1

110/12a-1

110/13-1

110/13-5

110/13-12

110/14-3

110/20-1

112/25a-1

113/26-1

113/27-3

Blakenhall-1

Boots Green-1

Burford-1

Elworth-1

Knutsford-1

Prees-1

Thistleton-1

APPENDIX II

Core and outcrop sedimentary logs (1:50 scale)

Key to lithologies, contacts and sedimentary structures

110/2-6

110/8a-5

110/13-5

110/14-3

Beeston Castle

Bromborough Beach

APPENDIX II (contd)

Burton Point

Carden Park

Fleswick Bay

Helsby Hill

Hilbre Point

Moss Farm

New Brighton

Raw Head

Saltom Bay

St Bees South Head

Thurstaston Road Cutting

APPENDIX III

Modal Analysis Data

110/2-6

110/8a-5

110/13-5

110/14-3

Lancashire

North Cheshire

North Wirral

South Cheshire

South Wirral

West Cumbria

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ICP-AES and ICP-MS Geochemical Data

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1. INTRODUCTION

1.1 REGIONAL SETTING

The Permo-Triassic basins of the British Isles are essentially post-Variscan structures that evolved in response to the very earliest stages of extension in what would become the NE Atlantic. These basins extend within Britain from the onshore Wessex and Worcester Basins in southern England, through the Stafford and Cheshire Basins of central and NW England to the mainly offshore East Irish Sea, Solway and North Channel Basins lying between England, Scotland and Ireland. Originally thought to form a near linear trend, these basins were termed the 'Clyde Belt' by Maclean (1978) although subsequent offshore exploration for hydrocarbons has rendered the term somewhat obsolete. The present-day Permo-Triassic basins in and around the British Isles (Figure 1.1) form the remnants of a previously more extensive Permo-Triassic cover that preserve, on the western side of the British Isles at least, a broadly similar sedimentary succession. This may imply connected depositional basins from southern England and north west France certainly as far north as the East Irish Sea and Solway Basins and possibly further north. This concept of a series of basins with a related sedimentary history developed progressively through the 1960s and 1970s, partly in response to an increasing interest in hydrocarbon exploration, with the model of linked structural basins being expounded by Audley-Charles (1970) and supported by Ziegler (1987), while that of a through-flowing fluvial system was first suggested by Wills (1970).

The present study is concerned principally with two of these basins, the Cheshire and East Irish Sea Basins lying both onshore and offshore NW England, and in particular with the sandstone dominated succession of the Sherwood Sandstone Group which forms the Early Triassic (Scythian to early Anisian) fill within these basins (Figure 1.2). These two basins preserve a continuous Sherwood Sandstone Group succession that varies from more than 1km in thickness in the central parts of both basins to less than 500m across the basement rise that separates them and thins to a feather edge in response to erosion at the present-day surface around many of the basin margins (see Sections 1.3 and 2.3 below). In practice it is difficult to completely divorce the Sherwood Sandstone Group from the underlying Permian successions and the overlying Mid-Late Triassic Mercia Mudstone Group such that some discussion of these is necessary in order to both constrain the Sherwood

Figure 1.1 British Isles with an outline of present day Permo-Triassic Basins

Sandstone Group stratigraphy and to place it in a regional context (see especially Section 2.3 on the well stratigraphies).

In total, the East Irish Sea and Cheshire Basins contain a Permian to Early Jurassic sedimentary fill that ranges up to more than 4km in preserved thickness, the majority of which is of Triassic age and comprises red-bed sequences with continental and marginal marine affinities. Mainly Early Permian continental deposits, including aeolian sandstones with associated alluvial fan, wadi and playa lake sediments, locally exceed 500m in thickness in the Cheshire Basin (wells Knutsford-1 and Prees-1) and 800m in the East Irish Sea Basin (well 110/13-12) but are preserved within restricted sub-basins beneath the Triassic succession such that they are locally absent with Triassic rocks resting directly on the underlying Carboniferous or older rocks (Tonks *et al.* 1931; Poole and Whiteman 1955). Within the East Irish Sea Basin and northern parts of the Cheshire Basin a marginal to locally fully marine Late Permian succession of claystones and evaporites oversteps the Early Permian sandstones and passes gradationally upwards into sandstones of latest Permian to earliest Triassic age.

The Triassic succession of NW England comprises in general a lower arenaceous interval referred to the Sherwood Sandstone Group and an upper argillaceous/saliferous interval referred mainly to the Mercia Mudstone Group but also locally including the Penarth Group of Rhaetian age (see Figure 1.2 and discussion in Section 2.3). Jurassic sediments representing marine to marginal marine environments and with a rich faunal assemblage indicating a Liassic (Hettangian to Pliensbachian) age are known from a series of outliers. These occur principally within the southern parts of the Cheshire Basin near Prees (Wem-Audlem sub-Basin) and in the Keys sub-basin, which forms a north western part of the East Irish Sea Basin, lying to the east of the Isle of Man. Several smaller outliers are recorded (Warrington 1997) across NW England, within the East Irish Sea Basin and into Northern Ireland where, in the latter instance, they are overlain by a thin Cretaceous interval and Tertiary basalts. No sedimentary sequences younger than Liassic (excepting Quaternary tills) are, however, known from the Cheshire and East Irish Sea Basins although the pre-Tertiary presence of younger Jurassic and Cretaceous successions has been postulated in support of various models regarding Early Tertiary uplift (e.g. Green 1986; Green *et al.* 1997; Lewis *et al.* 1992; Cope 1997).

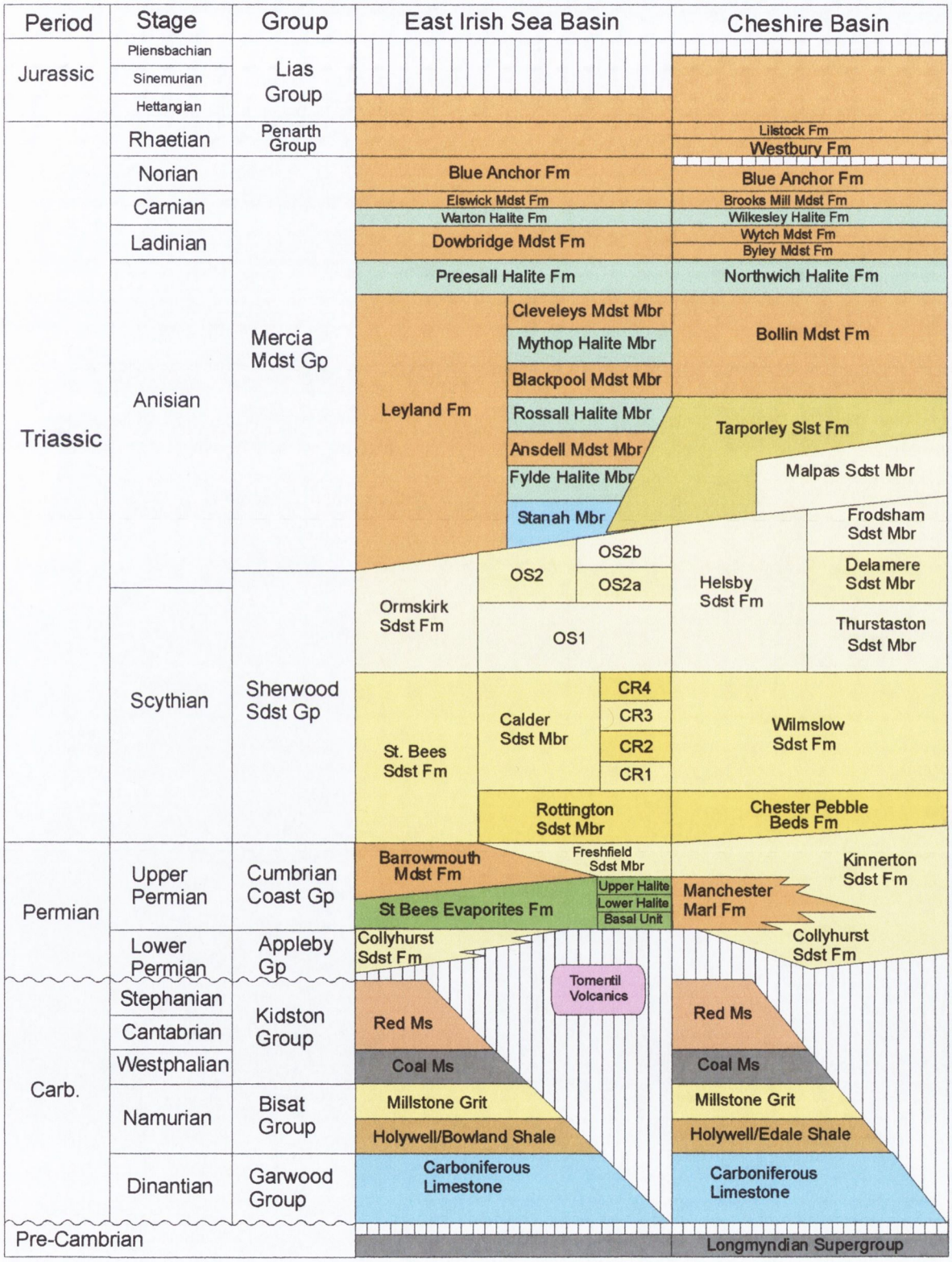


Figure 1.2: Stratigraphy of NW England and the East Irish Sea (after Jackson and Johnson 1996; Wilson 1990; 1993)

Underlying the Permo-Triassic basins is a variably thick Carboniferous succession comprising Dinantian, Namurian and Westphalian sedimentary sequences that are substantially affected by late-Carboniferous (Variscan) folding and faulting. The deposition of the Carboniferous can be related to the infilling of the Pennine Basin (Besly 1988) or Central Province (Collinson 1988) of northern England. The greatest thickness of Carboniferous sediments occurs in the Manchester area where some 6kms are preserved although this does not necessarily reflect the location of a Carboniferous depocentre. The succession generally comprises marine limestones within the Dinantian interval, basinal claystones and fluvio-deltaic sandstones in the Namurian and deltaic to delta plain sandstones, claystones and abundant coals within the Westphalian although this succession passes upwards into red-bed sandstones and claystones within parts of Lancashire and Staffordshire.

The Carboniferous sequences have been extensively eroded, both as a result of Variscan inversion and at the present day erosion surface, such that Westphalian and Namurian successions have been removed entirely to expose Dinantian limestones in large areas of the Ribblesdale Fold Belt (Gawthorpe 1987) of central Lancashire, North Wales and the southern Pennines where they form the outcrops of the Peak District. The Carboniferous rocks, and their distribution, achieve economic importance due to the presence of highly organic-rich shales within the uppermost Dinantian and lower Namurian and to the extensive coal seams within the Westphalian. As well as the long history of coal extraction in the area, these sequences have provided the source rocks for oil and gas generation and have been tied geochemically to the hydrocarbons trapped within the Sherwood Sandstone Group reservoirs in the offshore East Irish Sea Basin (Armstrong *et al.* 1997).

Carboniferous sequences are absent from the southern parts of the Cheshire Basin where the presumed Triassic sandstones rest directly upon Silurian to Ordovician metasediments and, locally, on metavolcanics and metasediments of the Precambrian Longmyndian Supergroup.

1.2 EXISTING STRATIGRAPHIC NOMENCLATURE

The currently accepted stratigraphic nomenclature for the Triassic successions of NW England has effectively evolved from that established in the 19th Century for the Triassic

of northern Europe. Early workers, including Binney (1839), Ormerod (1848) and Hull (1860; 1869), attempted to subdivide the British Triassic into equivalents of the tripartite Bunter, Muschelkalk and Keuper of northern Germany despite significant problems in establishing a direct correspondence of lithostratigraphical units. Hull (1869), in particular, identified an Early Triassic Bunter and a Late Triassic Keuper (Figure 1.3) with the boundary between the two lying within the Lower Triassic arenaceous succession and being identified on the basis of the presence or absence of pebbles, the colour and the relative hardness of the rocks. The upper succession was therefore divided into a lower Keuper Sandstone overlain by a Keuper Mudstone. The base of the Keuper Sandstone was placed at a prominent break in the Cheshire Basin succession marked by extremely pebbly sandstones which appeared at the time to be unconformable on underlying less pebbly sandstones. In the absence of a well defined Muschelkalk equivalent this boundary was equated to the Hardegsen Unconformity of mainland NW Europe, it being presumed that both the Muschelkalk and the Röt Halites together with their associated claystones had been eroded, and the underlying sandstones were assigned to the Bunter. The fact that the Hardegsen Unconformity directly overlies and partially cuts out the Bunter Sandstone in the Germanic Triassic nomenclature (Trusheim 1963), and is therefore beneath the Muschelkalk and Röt Halites and Mudstones, does not appear to have been of much concern.

Additionally, Hull (1869) subdivided the Bunter Sandstone into three units comprising the Lower Mottled Sandstone, Pebble Beds and Upper Mottled Sandstone (Figure 1.3), the defining criterion being the relative abundance of pebbles within the sandstones of the Pebble Beds. These terms, together with the Keuper Sandstone and Mudstone, persisted until a review of Permian stratigraphy in the area (Smith *et al.* 1974) recognised the problems of defining and identifying a Permo-Triassic boundary, especially where the marine to marginal marine Late Permian claystones, termed the Manchester Marl Formation, are absent (Figure 1.2). This latter succession, related to the Bakevellia Sea transgression and equivalent to Zechstein EZ1-EZ3 based on the bivalves *Bakevellia*, *Permophorus* and *Schizodus* (Arthurton *et al.* 1978), provides a reasonable marker horizon throughout much of the East Irish Sea Basin and in north eastern parts of the Cheshire Basin but is absent (?non-depositional) from large areas in the western and southern Cheshire Basin. Smith *et al.* (1974) formalised the previously local term 'Collyhurst

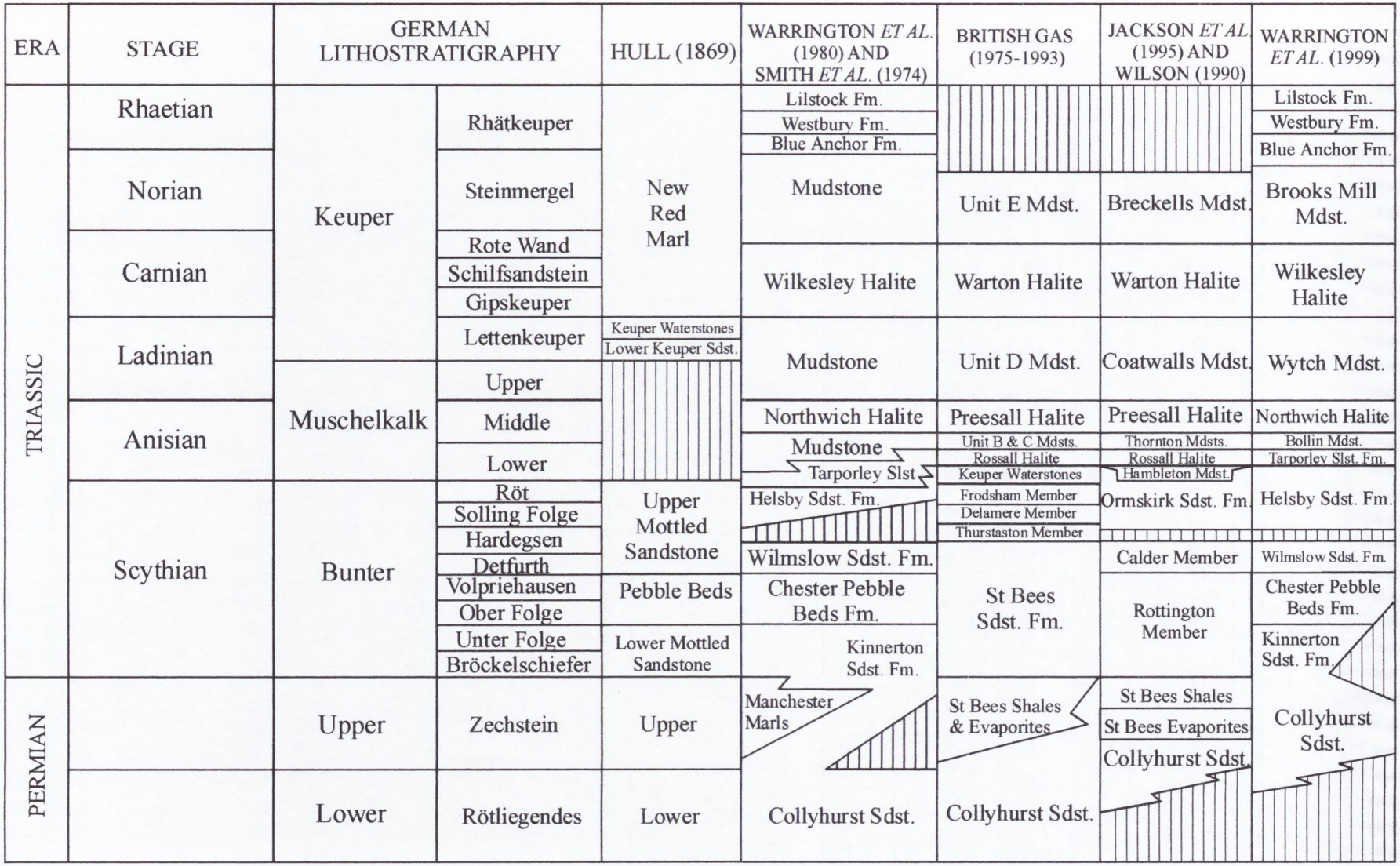


Figure 1.3 Evolution of stratigraphic nomenclature for the Triassic and Permian in NW England and the East Irish Sea (Hull 1869, Warrington *et al.*1980, Smith *et al.* 1974 and Warrington *et al.* 1999 refer principally to the Cheshire Basin, while British Gas publications, Jackson *et al.*1995 and Wilson 1990 refer mainly to the offshore East Irish Sea Basin). See Figure 1.2 for details of current nomenclature.

Sandstone' Formation for the arenaceous interval below the Manchester Marl and used the boundary between the two to define the Upper and Lower Permian. The top of the Permian, however, remained a problem as the Manchester Marl passes upwards into barren claystones, siltstones and ultimately sandstones of the then presumed Triassic Lower Mottled Sandstone. Smith *et al.* (1974) proposed a solution by following earlier informal suggestions that the boundary lay somewhere within this succession (e.g. Tonks *et al.* 1931; Taylor *et al.* 1963) but placed the formal boundary at the nearest identifiable marker horizon on the base of the overlying Pebble Beds. The result of this suggestion was the transposition of the previously Triassic Lower Mottled Sandstone into the Permian as a consequence of the perceived need for an identifiable boundary between the systems.

The later re-naming of the Lower Mottled Sandstone as the Kinnerton Sandstone Formation (Warrington *et al.* 1980) and its extension downwards to the Carboniferous unconformity in areas where no Manchester Marl could be identified provided a more realistic resolution. It was then recognised that the Kinnerton Sandstone Formation may well span the Permian to Triassic boundary and that it is not possible in the field or in wells to define any horizon that may separate Permian from Triassic sequences (Figure 1.3).

Warrington *et al.* (1980) also introduced the term Sherwood Sandstone Group for the lower Triassic arenaceous succession and renamed the subdivisions; the Keuper Sandstone becoming the Helsby Sandstone Formation, the Upper Mottled Sandstone becoming the Wilmslow Sandstone Formation and the Pebble Beds being formalised as the Chester Pebble Beds Formation (Figures 1.2 and 1.3). On the basis of published palynological data (Warrington 1967; Warrington 1970a; Warrington 1970b) Warrington *et al.* (1980) appreciated that the terms Keuper and Bunter were inappropriate to the Triassic of NW England and should be discarded. This decision stemmed primarily from the growing body of data becoming available at the time from the southern North Sea that provided a link with the Germanic sequences and showed that the lithostratigraphic correlations were fundamentally flawed. Of particular relevance to the Sherwood Sandstone, the palynological data showed that the previously designated base of the Keuper was in fact Scythian in age and therefore pre-dated the Germanic Keuper, Muschelkalk and Upper Bunter (Warrington *et al.* 1980). In addition, these authors formalised the terms Frodsham, Delamere and Thurstaston Members as subdivisions of the Helsby Sandstone Formation.

These members had been introduced by Thompson (1970a) as lithostratigraphical units based upon lithofacies identified in outcrops and boreholes across north Cheshire and south Lancashire in what, at the time, was the first serious attempt at a sedimentological description of the Early Triassic sandstones (see Section 1.4 below).

The top of the Sherwood Sandstone Group also provided its own measure of confusion, due in part to the changing nature across NW England of the contact between the sandstones and the overlying predominantly mudstone and evaporite succession which had been formalised as the Mercia Mudstone Group (Warrington *et al.* 1980). In the northern parts of the Cheshire Basin this lithological transition is marked by the presence of a silty sequence within the base of the Mercia Mudstone Group originally referred to as the Waterstones (Pocock and Wray 1925), a term originally introduced by Smith (1815) for any strata in which springs are numerous. Southwards the Waterstones, renamed the Tarporley Siltstone Formation by Warrington *et al.* (1980), becomes arenaceous and had been referred to locally as the Malpas Sandstone (Poole and Whiteman 1966), a term left as an informal member of the formation by Warrington *et al.* (1980), such that the boundary between the Sherwood Sandstone Group and the Mercia Mudstone Group becomes difficult to ascertain with any certainty.

This problem was exacerbated with the discovery in 1974 of the offshore Morecambe Gas Field and the identification by the operators, Hydrocarbons Great Britain (later British Gas), of four intervals recognised from wireline data within the uppermost Sherwood Sandstone reservoir. It was thought that these informal units could be recognised and correlated across the field and were therefore named, from the onshore usage, the Thurstaston, Delamere, Frodsham and Keuper Waterstones Members (Figure 1.3). The need for a fourth name therefore transposed a formation at the base of the Mercia Mudstone Group in the onshore Cheshire Basin into a member at the top of the Sherwood Sandstone Group in the offshore East Irish Sea Basin. Although no longer accepted in the stratigraphical nomenclature, the term Keuper Waterstones continued in references from British Gas where it is enshrined in the Annex B submission to the Department of Energy and in publications from British Gas personnel (e.g. Bushell 1986; Stuart and Cowan 1991; Cowan *et al*, 1993). Subsequent to this the discovery of both oil and gas accumulations in the southern part of the East Irish Sea Basin by Hamilton Oil Company (later BHP

Petroleum) within an uppermost Sherwood Sandstone Group reservoir with three readily identifiable subdivisions resulted in the abandonment of the 'Keuper Waterstones' as a stratigraphic unit, at least in these areas (Yaliz 1997; Haig *et al.* 1997).

The most recent revisions of the Triassic stratigraphy, and the currently accepted lithostratigraphical nomenclature (Figure 1.2), broadly follow the principles laid down by Warrington *et al.* (1980) with some modifications based largely on the increased data from the offshore areas in response to oil and gas exploration. The Mercia Mudstone Group stratigraphy has been refined by Wilson (1990; 1993), with formation and member names being allocated to identifiable claystone dominated and halite dominated units, while the existing nomenclature for the Sherwood Sandstone Group has only been modified for the offshore areas of the East Irish Sea Basin. Here the Ormskirk Sandstone Formation becomes the offshore equivalent of the onshore Helsby Sandstone Formation, while the Calder and the Rottington Sandstone Members of the St Bees Sandstone Formation equate respectively to the onshore Wilmslow Sandstone and Chester Pebble Beds Formations (Jackson and Mulholland 1993; Jackson and Johnson 1996; Jackson *et al.* 1997). The offshore Ormskirk Sandstone Formation is further subdivided from the base into units OS1, OS2a and OS2b that broadly equate to the Thurstaston, Delamere and Frodsham Members respectively of the onshore in the northern Cheshire Basin and the offshore in the BHP operated oil and gas fields in the southern East Irish Sea Basin.

This relatively simplistic equivalence of the members within the Ormskirk and Helsby Sandstone Formations is, however, complicated by comments in Warrington *et al.* (1999), the most recent pronouncement on the Sherwood Sandstone from the British Geological Survey. These authors, while officially retaining the Thurstaston, Delamere and Frodsham Sandstone Members of the Helsby Sandstone Formation in the Cheshire Basin, add that recent mapping by the BGS in the Chester and Nantwich areas of the basin (west central parts of the Cheshire Basin) has placed the base of the Helsby Sandstone Formation at the unconformable base of the Delamere Sandstone Member. This therefore consigns the Thurstaston Sandstone Member to the Wilmslow Sandstone Formation but no attempt is then made to provide criteria that distinguish the base of the Thurstaston Sandstone Member or to differentiate it from the underlying remainder of the Wilmslow Sandstone Formation.

1.3 BASINAL STRUCTURE

The contiguous Permo-Triassic basins of NW England are defined and controlled by mainly N-S and NNW-SSE trending fault systems with subsidiary faults trending NE-SW and E-W (Figure 1.4). To the south east the Cheshire Basin connects over the present-day Hodnet Horst with the similarly Permo-Triassic Stafford Basin, while northwards the East Irish Sea Basin is separated from the Solway Basin by the present-day Ramsey-Whitehaven Ridge with a thin veneer of Sherwood Sandstone Group sandstones preserved over the crest of this structure. Structurally, the East Irish Sea and Cheshire Basins are separated by a broad anticlinal ridge, the Ellesmere Saddle of Chadwick *et al.* (1999) and the Llyn-Rossendale Ridge of Jackson and Mulholland (1993), the latter term being preferred and adopted herein. For the purposes of this study the divide between the Cheshire and the East Irish Sea Basins is presumed to lie across the north central area of the Wirral (following Jackson and Mulholland 1993) such that outcrops in Lancashire (Greetly Hill) and in the north of the Wirral (e.g. New Brighton, Hilbre Point and Thurstaston) are presumed to lie within the East Irish Sea Basin, while those in the south of the Wirral (e.g. Bromborough Beach and Burton Point) are presumed to lie within the Cheshire Basin (Figure 1.5) although the demarcation line is necessarily arbitrary. These present-day structures that form approximate boundaries between the basins are also inferred to have been present during Sherwood Sandstone deposition from the comparative thickness of the Early Triassic succession within the basins and across the basin margins.

1.3.1 The Cheshire Basin

The Cheshire Basin is broadly elongate with a long axis orientated approximately NNE-SSW and is bounded to the E and SE by a major fault system comprising the Red Rock, Wem and Hodnet Faults. The present-day structural configuration of the Cheshire Basin has been determined from a combination of surface mapping, borehole data and geophysical surveys including gravity, magnetics and, latterly, seismic data acquired principally in the search for hydrocarbons. Early workers identified little more than the outline of the basin (Hull 1869), while the large scale half-grabenal profile into the eastern bounding faults was delineated during an IGS resurveying of the 1950s and 1960s (Poole and Whiteman 1955; Taylor *et al.* 1963; Evans *et al.* 1968) using mainly gravity and magnetic data. These workers recognized that there was considerable relief on the sub-Permian surface but it was not until the availability of more modern seismic data that a

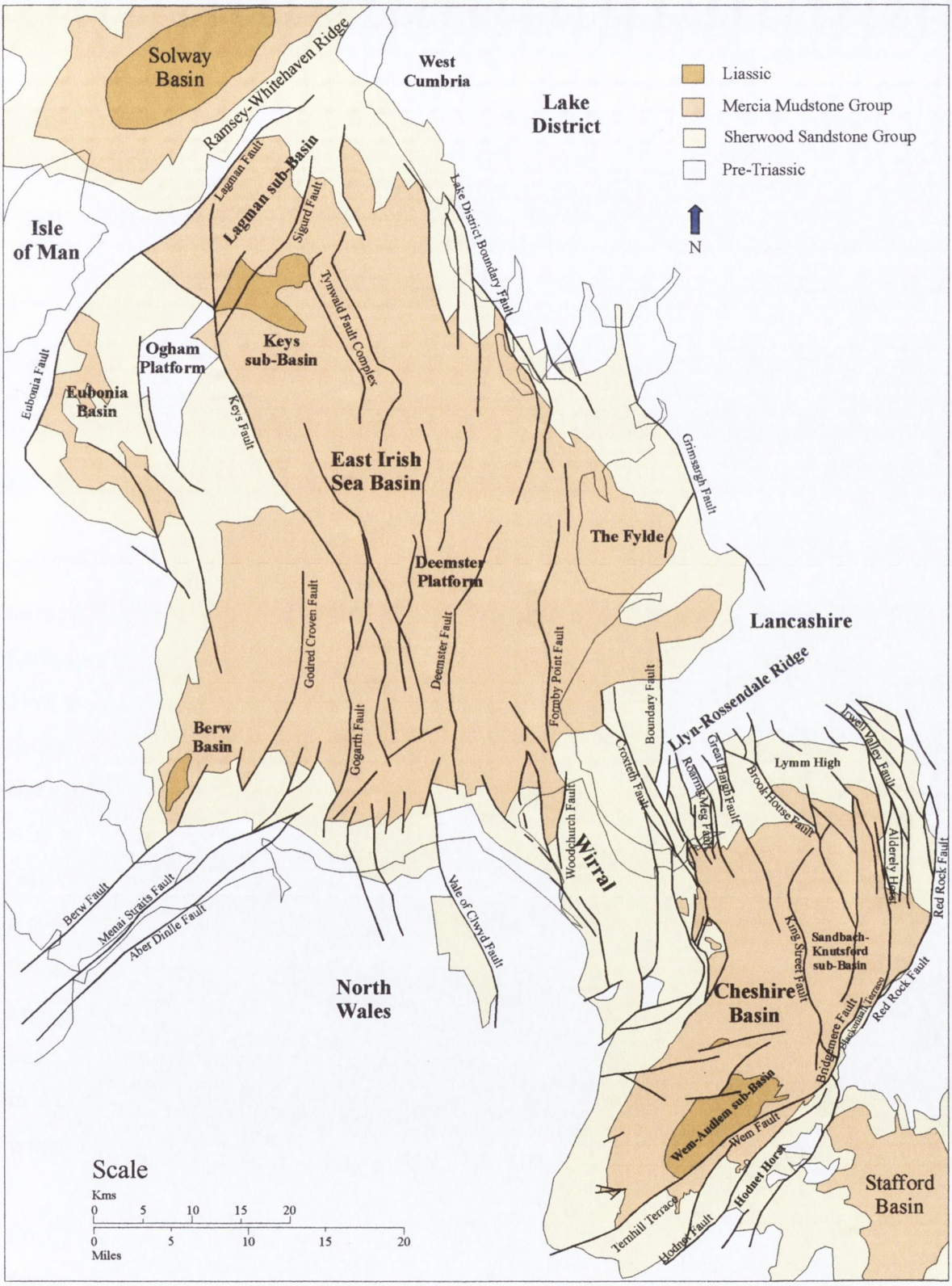


Figure 1.3 Generalised present-day structure of the East Irish Sea and Cheshire Basins (after Jackson and Mulholland 1993; Jackson *et al.* 1995; Chadwick *et al.*1999)

series of complex structures both at the Permian/Carboniferous interface and within the Permo-Triassic succession could be recognised (e.g. Smith *et al.* 1980; Lamb *et al.* 1983; Gale *et al.* 1984; Mikkelsen and Floodpage 1997).

In the extreme NE of the Cheshire Basin a complex graben extends approximately northwards parallel to the Red Rock Fault and then NW between this and the Irwell Valley Fault. Within this structure a variable but generally thick Collyhurst Sandstone Formation, up to 330m thick (Poole and Whiteman 1955), is overlain by the Late Permian Manchester Marl which is in turn overlain by a Sherwood Sandstone succession that appears from seismic data to be thinner than that preserved to the S and W (Mikkelsen and Floodpage 1997; Chadwick *et al.* 1999). Southwards this structure shallows and merges with the Alderley Horst (Chadwick *et al.* 1999) which is in turn lost into the hangingwall of the Red Rock Fault.

Westwards across this northern part of the Cheshire Basin a broad faulted structural high, termed the Lymm High by Chadwick *et al.* (1999), preserves a significantly thinner Collyhurst Sandstone Formation. The Early Permian sandstones are generally less than 10m thick and are locally absent with the Manchester Marl lying directly on Carboniferous rocks. The Sherwood Sandstone Group in this area thickens progressively southwards into the central parts of the basin where it is dissected by the N-S trending King Street Fault which throws down eastwards into the Sandbach-Knutsford sub-Basin of Chadwick *et al.* (*op. cit.*). Further west a significant thickness of Collyhurst Sandstone is preserved within a series of complex half graben bounded by generally NNW-SSE trending faults including the Brook House, Roaring Meg and Great Haigh Faults. Modern seismic data (Mikkelsen and Floodpage 1997; Chadwick *et al.*, *op. cit.*) suggests that the majority of these faults have controlled both Permian and Early Triassic sediment thicknesses although the effect is noticeably most pronounced in the Early Permian Collyhurst Sandstone Formation within these northern parts of the basin.

Southwards the overall half grabenal configuration of the Cheshire Basin becomes more pronounced with significant thickening into the NE-SW to NNE-SSW trending Wem-Bridgemere-Red Rock Fault System. This fault system has present day normal throws in excess of 2500m. at the base Permo-Triassic level (Chadwick *et al.*, *op. cit.*), while the

Wem-Audlem sub-Basin in the hangingwall preserves the greatest total thickness of sediment, including Liassic sequences, in the basin with the pre-Permian basement at a depth of more than 4500m. Conversely, parts of this same sub-basin form a local structural high at Mercia Mudstone Group level suggesting the presence of a Sherwood Sandstone Group depocentre that has undergone subsequent, and significantly more, uplift than surrounding areas. This supposition is supported by depth of burial and back-stripping studies which suggest locally strong syn-depositional control on Sherwood Sandstone Group sedimentary thicknesses (Chadwick *et al.*, *op. cit.*) in the hangingwall succession. Whether the Sherwood Sandstone Group was ever deposited, or temporarily preserved, on the footwall of the Red Rock Fault is unknown due to erosion at the present-day surface but a considerably thinned succession is preserved further S across the Hodnet Horst in the footwall of the Hodnet Fault (Figure 1.4).

To the W and SW both Permian and Triassic successions thin towards the generally unfaulted western basin margin, mainly in response to present day erosion but also partly due to stratigraphical attenuation. The S and SE margins of the Cheshire Basin comprise a series of terraces demarcated by the Wem, Bridgemere and Hodnet Faults and by splays off these major faults. The two most significant of these terraces, the Ternhill and Blackenhall Terraces, effectively define the basin margin in this area. The Ternhill Terrace exposes Sherwood Sandstone Group sequences that thin south and east towards a number of Carboniferous inliers, while the Blackenhall Terrace further north lies in the hangingwall of the Red Rock Fault and preserves approximately 1000m of Sherwood Sandstone Group beneath a relatively thin cover, due to present day erosion, of the Mercia Mudstone Group.

1.3.2 The East Irish Sea Basin

The major and deeper parts of the East Irish Sea Basin lie offshore and have been divided into northern and southern provinces (Jackson *et al.* 1987; Jackson and Mulholland 1993; Jackson *et al.* 1995), while thinner sequences are preserved around the basin margins onshore in west Cumbria, south Lancashire and North Wales as well as offshore in the footwall of the major faults. The majority of these thin marginal sequences are inferred to be erosional remnants although some stratigraphic thinning is observed on seismic data towards the western and southern limits of the Sherwood Sandstone Group (Jackson and

Mulholland 1993) and in the Sellafield area of west Cumbria where the Lake District Lower Palaeozoic Block is regarded as having been a positive feature from the Early Carboniferous onwards (Chadwick *et al.* 1994).

The northern province is bounded by a series of broadly orthogonal faults trending NNW-SSE and NE-SW and preserves the thickest known successions of both the Sherwood Sandstone and the Mercia Mudstone Groups with a combined 5000-6000m in the Keys sub-Basin. These faults include the Lagman and Sigurd Faults in the N bounding the Ramsey-Whitehaven Ridge, the Keys Fault to the W and the Lake District Boundary Fault to the E. Within this area large westerly tilted fault blocks are separated by NNW-SSE trending fault complexes with fault planes dipping at relatively shallow angles to the east. Some of the displacement on these faults appears to be accommodated by detachments within Upper Permian halites (Jackson *et al.* 1995). The majority of the faults show evidence of syn-depositional movement during Sherwood Sandstone Group time with the greatest thickening being recorded into the hangingwalls of the Keys and Lake District Boundary Faults. The Ramsey-Whitehaven Ridge, the present-day divide between the East Irish Sea and Solway Basins, was also a structural high during the Early Permian (Jackson and Mulholland 1993) but was progressively onlapped and now preserves a highly attenuated Late Permian to Early Triassic succession.

The central part of this northern province includes the complex anticlinal horst within which the Morecambe Fields are situated. This structure has been interpreted as an elongate rollover positioned above a listric detachment in the Permian halites (Knipe *et al.* 1993). Northwards this structure degenerates into the Tynwald Fault Complex, described by Jackson *et al.* (1995) as a high level graben with minimal down to the east displacement at top Carboniferous level and interpreted as a post-depositional collapse structure. Adjacent to this fault complex and throughout the deeper parts of the northern province the halites in the lower succession of the Mercia Mudstone Group have been subject to halokinesis with numerous salt diapirs and pillows disrupting the overlying rocks.

Permian halites are largely absent from the southern province of the basin and faults are mainly steeply dipping and normal such that they define N-S trending horsts, graben and half-graben. Many of these faults appear to be post-depositional in origin and an overall

eastwards thickening is recorded on seismic data from the present day erosional feather edge of the Sherwood Sandstone Group in the W towards the major syn-depositional Formby Point Fault close to the Lancashire Coast in the E (Jackson *et al.* 1995). Counter to this overall trend there is some westward thickening of the Sherwood Sandstone Group into the down-to the-east Gogarth Fault. The recognition of fault control on Sherwood Sandstone Group preservation runs counter to the findings of Williams and Eaton (1993) who infer no active syn-sedimentary faulting during Sherwood Sandstone depositional time. These authors, however, examined a somewhat limited seismic database that did not include lines across the Formby Point Fault or within the deeper parts of the basin.

In the extreme S of the East Irish Sea Basin many of the N-S trending faults swing SW to become sub-parallel to the major Caledonide trending Berw and Menai Straits Faults that in part define the coast of North Wales. The entire Permo-Triassic succession thins towards this southern margin of the basin, mainly due to erosion at the present day surface but also partly in response to stratigraphic attenuation. This thinned succession can be traced onshore onto the Llyn-Rossendale Ridge running NE-SW through the Wirral and South Lancashire where it connects with Cheshire Basin and also into the Vale of Clwyd half graben in North Wales. The attenuation of the Sherwood Sandstone Group onto the Llyn-Rossendale Ridge, in particular, is recorded by Jackson *et al.* (1993) who cite this as evidence that this feature remained relatively positive throughout Permian to Triassic deposition.

There is extensive evidence for post-Triassic inversion in both the East Irish Sea and Cheshire Basins. The better quality and density of seismic data in the offshore areas, however, allows more accurate definition of structures. Many of the more significant, initially normal, faults have undergone compressional reactivation with the formation of ramp anticlines such as that hosting the Morecambe Field and hangingwall inversion structures such as those associated with the Formby Point Fault, one of which provides the trap for the Lennox Field (Haig *et al.* 1997). Local horsts cored by Carboniferous and older rocks including the Deemster and Ogham Platforms have also been interpreted as inversion structures (Jackson *et al.* 1995). The timing of any inversion remains uncertain due to the absence of post-Liassic sequences (apart from Quaternary tills) although basin modelling and regional mapping have suggested two episodes in the late Jurassic and Late

Cretaceous/Early Tertiary (Hardman *et al.* 1993; Cope 1994; 1997), while Ziegler (1987) also suggested intra-Cretaceous wrench faulting as a significant component.

1.4 PREVIOUS SEDIMENTOLOGICAL WORK

Prior to the pioneering work of Thompson (1969; 1970a) there were few attempts to describe the sedimentary characteristics of the Sherwood Sandstone Group and little understanding of the depositional environments responsible. Although there had been a recognition of aeolian influences in the sandstones, mainly in response to the presence of typically aeolian 'millet seed' grains (Shotton 1937), the principal concerns of earlier workers were stratigraphic rather than sedimentological. Consequently, various parts of the Sherwood Sandstone Group had been referred to deposition within a desert (Wedd *et al.* 1923), in a shallow sea (Sherlock 1926), under 'aqueous conditions' (Rice 1939a), within an inland lake (Wills 1948) and by ephemeral sheetfloods under predominantly arid conditions (Taylor *et al.* 1963). Descriptions of particular sedimentary structures, for example contorted bedding in the road cutting at Thurstaston on the Wirral (Rice 1939b), had been described in some detail but suggestions as to the sedimentary environment are sparse in the discussion.

Thompson (1969) described in detail the Sherwood Sandstone Group outcrops around Frodsham in the northwest part of the Cheshire Basin, interpreted the dominantly sandstone successions as being the product of aeolian dune migration and ascribed them to the 'Frodsham Member' of the then Keuper Sandstone (later re-named the Helsby Sandstone Formation). On the basis of the sedimentary structures recorded and comparison with descriptions of modern aeolian dunes (e.g. McKee 1966), Thompson (1969) also suggested a range of dune morphologies, notably including transverse dunes as the most common type, together with inferred palaeo-winds from the E. These suggestions, based at the time on rather limited outcrop data, have been subsequently corroborated by more extensive studies involving outcrops and shallow boreholes (Warrington *et al.* 1999) and on dipmeter data from offshore wells (Cowan *et al.* 1993). Further description and interpretation of lithofacies within the Keuper Sandstone (Helsby Sandstone Formation) led Thompson (1970a and 1970b) to identify low to moderate sinuosity fluvial channel and lacustrine deposits, using these to erect an informal stratigraphy based upon the sedimentological criteria. Thompson (1970a) also recognised

a significant difference in the Sherwood Sandstone Group succession in the southern parts of the Cheshire Basin where fluvial channel sequences appeared to be absent.

Sedimentological interpretations based on data from offshore wells drilled during the 1970's and 1980's was relatively sparse, serving only to confirm existing suggestions regarding the dominant fluvial facies associations, with the major emphasis at the time being on the petrographic and diagenetic aspects of the Morecambe Field (Woodward and Curtis 1987; Macchi *et al.* 1990). The full extent of aeolian deposits within the offshore successions began to be appreciated with renewed exploration activity in the early 1990's and the access that this brought to well cores across a wider geographical area of the East Irish Sea Basin (e.g. Cowan 1993; Meadows and Beach 1993a). Meadows and Beach (1993a), in particular, identified sedimentary characteristics indicative of a range of aeolian bedforms including barchan or parabolic dunes and wind rippled aeolian sandsheets controlled by changes in a relatively high palaeo-water table. Meadows and Beach (*op. cit.*) also proposed a semi-regional sedimentological model that allowed for contemporaneous fluvial and aeolian deposition dependent on geographical location within the basin and inferred palaeo-topography.

At this time, a distinctive sedimentary facies comprising somewhat enigmatic irregularly flat laminated sandstones that had been identified interbedded with aeolian sequences was ascribed by most authors to sheetflood processes (Bushell 1986; Cowan 1993) or damp sandflat (Meadows and Beach 1993a). The first indications that some of these sandstones may have marine affinities was provided by a comparison with modern siliciclastic sabkhas (Herries and Cowan 1997) based on work in Saudi Arabia (Fryberger *et al.* 1983) and supported by the identification of primary evaporites in the East Irish Sea Basin (Thompson and Meadows 1997 and Section 3.3.6 below). Subsequent work has served only to confirm the previous interpretations of depositional environments (e.g. Jackson *et al.* 1997; Plant *et al.* 1999) but has done little to integrate these findings into a basinal model or to explain the variations in sedimentary facies both areally and stratigraphically through the Sherwood Sandstone Group succession.

1.5 OBJECTIVES OF THE STUDY

The principal objectives of the study are as follows:

to erect a consistent facies scheme for the Sherwood Sandstone Group that will allow comparison of successions at differing stratigraphic positions within the group and between outcrops and cored intervals from wells.

to interpret the sedimentary facies with a view to determining any climatic implications that can be drawn from the vertical association of the facies.

to determine the chemical and petrographical character of the sandstones through a sufficient vertical succession in order to elucidate any significant variations that may have stratigraphic implications. If such variations are present, to use these to establish new well correlations that may shed light on hitherto problematic differences in the sedimentary succession across the East Irish Sea Basin and, possibly, the Cheshire Basin.

to review existing models of stratigraphic architecture within the Sherwood Sandstone Group and to use the new well correlations to establish the extent, distribution and orientation of fluvial channels within a regional context.

to compare the stratal architecture of the Sherwood Sandstone Group in NW England with previously published models of continental sequence stratigraphy in order to determine which if any of these may have validity with respect to the East Irish Sea and Cheshire Basins.

1.6 DATA AVAILABLE TO THIS STUDY

With the notable exception of the coastal cliffs around west Cumbria, outcrops of the Sherwood Sandstone Group in NW England are sparse and tend to be limited in the amount of exposure that they offer. Across much of the Cheshire Basin the Triassic generally is covered by a variably thick veneer of Pleistocene glacial deposits and it is only where crags have formed along the crest of hills (e.g. Beeston, Helsby and Raw Head), usually due to a capping of quartz cemented fluvial sandstones in the footwall of a normal

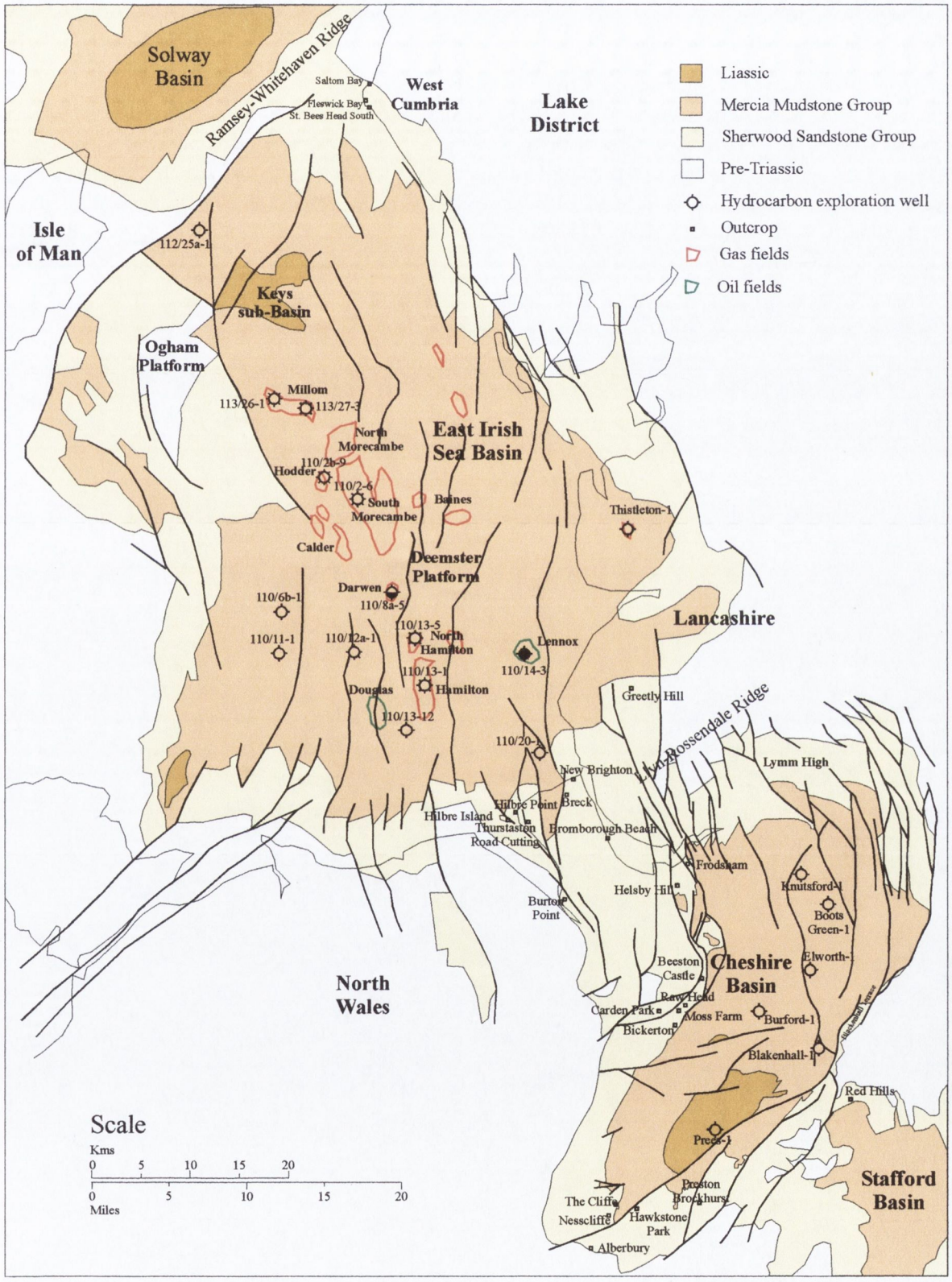


Figure 1.4 Locations of wells and outcrops in the East Irish Sea and Cheshire Basins

fault, that any reasonable vertical exposure can be found. Much of S and W Lancashire has no exposure at all, the Triassic rocks being blanketed by drift comprising glacial tills, peat and coastal sand dunes. Well data is also sparse in the Cheshire Basin, some six hydrocarbon exploration wells having been drilled to test the Sherwood Sandstone reservoir in the basin to-date. The number of wells drilled in the East Irish Sea Basin is significantly greater with more than 100 wells completed to-date, including appraisal and development wells in the various oil and gas reservoirs. Although many of these latter are now released into the public domain (access is granted six years after completion under U.K. legislation) there are still a considerable number of more recent wells that remain confidential.

Well data and outcrops examined during the course of this study are detailed below and located in Figure 1.5, together with the total amount of core or exposure sedimentologically logged (complete penetration by a well of the Sherwood Sandstone Group as currently defined is indicated by the suffix (P)). A number of oil and gas exploration companies have kindly supplied access to data and samples including BHP Billiton Petroleum Limited, BG Group plc, Burlington Resources (Energy Services) Inc., Centrica plc, EDC (Europe) Limited and Shell UK Limited. The sample locations for thin sections used to acquire petrographic data are shown on the 1:50 sedimentological logs, while both these and rock chips used to acquire whole rock geochemical data (supplied by Redrock Associates Limited) are detailed in the relevant appendix.

Wells	**Core depths (m)**	**Total Sherwood penetrated**	**Petrographic samples**	**Geochemical samples**	**Wireline data available**
Blakenhall	-	80.15m	-	-	γ and Δt
Boots Green	-	69.20m	-	-	γ and Δt
Burford	-	363.30m	-	-	γ and Δt
Elworth	-	99.67m	-	-	γ and Δt
Knutsford	-	1364.50m (P)	-	-	γ and Δt
Prees	-	1040.00m (P)	-	-	γ and Δt
Thistleton	-	718.40m (P)	-	-	γ and Δt
110/2-6	941.20-1202.60	289.85m	76	35	γ and Δt
110/2b-9	-	1271.30m (P)	-	-	γ, Δt, D. and N.
110/6b-1	-	1388.06m (P)	-	-	γ, Δt, D. and N.
110/8a-5	1231.30-1301.40	189.30m	5	44	γ and Δt

Continued

Wells	Core depths (m)	Total Sherwood penetrated	Petrographic samples	Geochemical samples	Wireline data available
110/11-1	-	1220.40m (P)	-	-	γ, Δt, D. and N.
110/12a-1	-	1222.85m (P)	-	-	γ, Δt, D. and N.
110/13-1	-	903.75m (P)	-	-	γ and Δt
110/13-5	853.25-963.40	244.15m	6	44	γ and Δt
110/13-12	-	1023.20m (P)	-	-	γ, Δt, D. and N
110/14-3	1068.00-1129.20	313.95m	11	51	γ and Δt
110/20-1	-	535.55m (P)	-	-	γ and Δt
112/25a-1	-	1186.70m (P)	-	-	γ
113/26-1	-	1471.55m (P)	-	-	γ, Δt, D. and N
113/27-3	-	1292.95m (P)	-	-	γ, Δt, D. and N

Outcrops	Vertical section logged	Petrographic samples
Alberbury	-	1
Beeston Castle	10.70m	2
Bickerton	-	2
Bromborough Beach	55.30m	2
Burton Point	101.90m	3
Carden Park	10.40m	3
Fleswick Bay	24.50m	4
Greetly Hill	-	1
Helsby Hill	47.00m	5
Hilbre Point (south)	9.90m	3
Hilbre Point (north)	8.40m	1
Hilbre Point (offshore)	8.00m	-
Moss Farm (north)	3.60m	-
Moss Farm (south)	4.70m	-
Nesscliffe	-	1
New Brighton (north)	3.50m	1
New Brighton (centre north)	3.80m	1
New Brighton (centre south)	3.80m	-
New Brighton (south)	3.90m	1
Preston Brockhurst	-	1
Raw Head	15.65m	4
Red Hills	-	3
Saltom Bay	26.25m	1
St Bees South Head	115.20m	1
The Cliffe	-	1
Thurstaston Road Cutting	19.35m	2

Other outcrops visited and examined but neither logged nor sampled include the Breck, Hilbre Island, Frodsham Village and Hawkstone Park.

Total logged section:	978.70m
Total number of petrographic samples	137
Total number of geochemical samples	174

Key to wirelines:

- γ – Gamma log
- Δt – Sonic log
- D – Density log
- N – Neutron log

2. WELLS

2.1 INTRODUCTION

The wireline data and existing stratigraphy for the wells listed in Section 1.5 are presented in Appendix I. Where available a wireline suite of gamma, sonic, density and neutron logs are plotted for the entire lower Triassic Sherwood Sandstone Group and Permian succession including the contact with the underlying Carboniferous rocks where these have been penetrated. Only the basal interval of the overlying Middle to Late Triassic Mercia Mudstone Group is plotted in order to establish the contact at the top Sherwood Sandstone Group surface. In a number of instances wells have not penetrated to the base of the Permo-Triassic succession and these wells are plotted to TD. In the case of the Prees-1 well in the Cheshire Basin no wireline data was directly available and a copy has been made from Warrington *et al.* (1999; Figure 11) that has been amended to the same scale as the other logs. For each well detailed in Appendix I the depths at which all identifiable groups, formations and members (taken where available from Well Completion Logs) were penetrated are shown in both imperial and metric measurements as both or either have been used in wells of differing vintages and/or were drilled by different operators. In addition, the penetrated thickness of each group, formation and member is shown in red with the unit name.

2.2 WIRELINE DATA

The wireline logs reproduced comprise, for the Sherwood Sandstone Group, the most stratigraphically useful suite of those generally run within hydrocarbon exploration, appraisal and development wells. The gamma, sonic and density logs, in particular, are lithology and facies sensitive in response mainly to changes in clay content, mineralogy, including particularly the percentage of K-feldspar, and diagenesis including preserved porosity. The density log, however, is subject to a gas effect (as are the gamma and sonic logs but to a lesser extent) that can be identified from the separation of the density and neutron logs. This effect is illustrated particularly well in the logs from well 110/13-1 from the top of the Sherwood Sandstone Group at 2510.0ft to approximately the base of the Ormskirk Sandstone Formation at 3051.0ft.

The units employed for each of the logs conform, for the most part, to hydrocarbon industry standards with gamma being measured as 0-150 in API units, sonic velocity as 40-

140 in microseconds/foot, density as 1.95-2.95 grams/cm^3 and neutron as 45 to -15 in standard porosity units. The scales used only vary from the norm in the cases of well Prees-1 where the gamma is show as 1-200 API, this being the scale used in Warrington *et al.* (1999), and well Thistleton-1 where the sonic is shown at 40-220 μsec/ft instead of the standard 40-140 μsec/ft due to the shallow and relatively unconsolidated nature of the Sherwood Sandstone Group succession in this well.

2.3 STRATIGRAPHY

The presently accepted stratigraphy of the Permian to Early Triassic succession in the Cheshire and East Irish Sea Basins has been largely defined from wireline log characteristics together with lithological data from core and cuttings material. While the gross stratigraphic differentiation of this succession is reasonably consistent across the area and through both basins there are clearly differences in detail that are not accounted for within the current nomenclature.

The presumed Early Permian Collyhurst Sandstone Formation (Figure 1.2), referred to the Appleby Group by Jackson and Johnson (1996), generally rests unconformably on Carboniferous rocks and is a predominantly aeolian sandstone with a uniformly low gamma and moderately high sonic response that reaches a known maximum thickness of 828.75m in well 110/13-12 where the base was not penetrated. The base of the formation where it is penetrated is generally easily recognisable from the sharp boundary to high gamma, high sonic velocity Carboniferous rocks (e.g. well Knutsford-1) except where there is a presumed water-lain succession at the base of the Collyhurst Sandstone with an irregular log response (e.g. well 110/13-1). The top of the formation, likewise, in the northern parts of the Cheshire Basin and southern parts of the East Irish Sea Basin is defined by a sharp upward increase in gamma to the overlying Manchester Marl and Barrowmouth Mudstone Formations respectively (e.g. well 110/13-1). Northwards in the East Irish Sea Basin this contact is replaced by that of the Collyhurst Sandstone Formation with halites and anhydrites (see below) of the St Bees Evaporites Formation. In the southern Cheshire Basin a definition of the top of the Collyhurst Sandstone Formation becomes more problematical as the Manchester Marl Formation becomes progressively sandier and is known locally as the Bold Formation (Warrington 1999) such that, as its difficult to differentiate the two (e.g. well Prees-1).

The evaporitic and argillaceous succession referred to the Cumbrian Coast Group (Jackson *et al.* 1997) of presumed Late Permian age comprises four formations that are, at least partially, coeval. The St Bees Evaporites Formation is present only in the north central parts of the East Irish Sea Basin and has been described in detail from outcrops and shallow boreholes around west Cumbria (Arthurton and Hemingway 1972). In well sections the formation reaches a maximum of 225.00m in well 112/25a-1 but thins southwards to 40.25m in well 110/12a-1 and is absent to the south and east of this well. The log character is distinctive with very low gamma, uniform sonic and low density responses suggesting that halite and anhydrite are the principal evaporite minerals present. This is overlain by the Barrowmouth Mudstone Formation and its lateral equivalent southwards, the Manchester Marl Formation, which reach maximum recorded thicknesses in the East Irish Sea and Cheshire Basins of 157.80m (well 110/110-1) and 135.00m (well Knutsford-1) respectively. The term Manchester Marl Formation has been applied to the Late Permian claystone succession in the southern parts of the East Irish Sea Basin (Jackson *et al.* 1997; Yaliz 1997; Haig *et al.* 1997) but herein it is restricted for clarity to the Cheshire Basin as, otherwise, the boundary between this and the Barrowmouth Mudstone Formation becomes impossible to define. The Barrowmouth Mudstone and Manchester Marl Formations exhibit the typical high gamma, high sonic velocity and inverse density/neutron separation of claystones that distinguishes them from the Collyhurst Sandstone and St Bees Evaporites Formations.

In the Cheshire Basin and the southern parts of the East Irish Sea Basin the Manchester Marl and Barrowmouth Mudstone Formations are overlain by a low gamma, low sonic sandstone interval that is referred to the Kinnerton Sandstone and Freshfield Sandstone Formations respectively. From outcrop data alone (see sedimentological log for Burton Point, Appendix II) these sandstones are presumed to be largely aeolian and, as a result of their log characteristics, serve to define the boundaries between these formations and the underlying argillaceous successions. The Freshfield Sandstone Formation thins northwards from 55.80m in well 110/13-12 to 6.10m in well 110/6b-1 and is absent further north such that the base of the Sherwood Sandstone Group rests directly on the Barrowmouth Mudstone Formation (e.g. well 110/2b-9).

The Sherwood Sandstone Group is subdivided into three units identifiable by broadly similar wireline log patterns in both the East Irish Sea and the Cheshire Basins. In the East Irish Sea Basin these are referred to the Rottington and Calder Sandstone Members of the St Bees Sandstone Formation and the Ormskirk Sandstone Formation, while in the Cheshire Basin they are referred to the Chester Pebble Beds, Wilmslow and Helsby Sandstone Formations (Figure 1.2). Notwithstanding the inconsistency of members in one basin being correlated with formations in the other, these stratigraphic units are seen as being broadly equivalent (Jackson and Johnson 1996 and Warrington *et al.* 1999).

The Rottington Sandstone Member and the Chester Pebble Beds Formation are sandstone dominated successions with a characteristically high gamma and high sonic log response that are assumed to be dominantly fluvial by comparison with their exposed equivalents in west Cumbria and at Burton and Bromborough Beach on the Wirral. Cuttings data from wells (obtained from well Completion Logs) together with sedimentary and petrographic data from the outcrops at St Bees South Head and Fleswick Bay indicate that the high gamma response is partly a function of a high K-feldspar content in the sandstones rather than their clay content alone (see Sections 3.2 and 4.2), while the high sonic velocity indicates low porosity, potentially related to high levels of cementation. The base of these units, and hence the base of the Sherwood Sandstone Group as currently defined (Jackson and Johnson 1996), is easily delineated in the presence of the Kinnerton and Freshfield Sandstone Formations due to the prominent log break in both gamma and sonic traces in response to an apparent change in both lithology and porosity (e.g. well 110/13-12).

Where the Kinnerton and Freshfield Sandstone Formations are absent, especially in the central and northern parts of the East Irish Sea Basin, the boundary becomes more problematical as the high gamma sandstones of the Rottington Sandstone Member overlie, or are interbedded with, high gamma claystones of the Barrowmouth Mudstone Formation (e.g. well 113/26-1). This succession is exposed at Saltom Bay in west Cumbria (see Saltom Bay sedimentological log, Appendix II, and discussion in Sections 3.6 and 8.3) where it is apparent that there is no easily defined boundary between the Sherwood Sandstone Group and the Cumbrian Coast Group. To some extent this problem is made apparent where density and neutron data is available (e.g. wells 110/2b-9 and 113/27-3) due to the inverse density/neutron separation that is a response to the highly argillaceous

rocks of the Barrowmouth Mudstone Formation. The exact location of a Sherwood Sandstone to Barrowmouth Mudstone boundary remains, however, ambiguous due to the interbedding of the two lithologies, as shown on the logs for well 113/27-3 where gamma and density/neutron responses show claystones interbeds present for nearly 400ft above the defined base of the Sherwood Sandstone Group.

The boundary between the Rottington Sandstone Member and the Calder Sandstone Member, equivalent and similar in character to that between the Chester Pebble Beds Formation and the Wilmslow Sandstone Formation, is marked by an upward drop in the gamma response and an even more dramatic break in the sonic velocity (e.g. well 113/26-1). This log break forms a significant seismic marker that has been mapped across the East Irish Sea Basin, referred to as the 'Top Silicified Zone' by Colter and Barr (1975), and has also been identified in the Cheshire Basin (Evans *et al.* 1993). Previously thought to be wholly diagenetic in origin (Colter and Barr 1975; Ebbern 1981) this boundary has subsequently been related to a facies change from dominantly fluvial sandstones below to sandflat, potentially aeolian, sandstones above as similar log characteristics are recognised in the Ormskirk Sandstone Formation where these can be tied to core-derived sedimentary facies (Meadows and Beach 1993a; Jackson *et al.* 1997). On the basis of these criteria the Rottington Sandstone Member varies between 202.90m thick (well 110/20-1 but see well Thistleton-1 where it is apparently absent) and 694.30m thick (well 113/26-1), while the Chester Pebble Beds Formation reaches a maximum recorded thickness of 490.00m in the Prees-1 well.

Log responses in the Wilmslow Sandstone Formation and its equivalent the Calder Member of the St Bees Sandstone Formation are significantly more varied with alternating intervals of high base line gamma coupled with uniformly high sonic velocity and low base line but erratic gamma coupled with lower and also erratic sonic (e.g. well 110/11-1). As with the contact at the base of this formation/member these log characteristics have been related to alternating sedimentary sequences dominated by fluvial channel sandstones and sandflat or aeolian sandstones respectively (Meadows and Beach 1993a; Jackson *et al.* 1997). However, as similar characteristics are carried up into the overlying Helsby and Ormskirk Sandstone Formations (see below), definition of the top of the Wilmslow/Calder can be problematical. This boundary has, however, been identified by several authors as a

major intra-Sherwood Sandstone Group unconformity (e.g. Colter and Barr 1975; Bushell 1986; Evans *et al.* 1993) which is equated with the Hardegsen Unconformity of the southern North Sea. Evans *et al.* (1993, Figure 8) identify this unconformity on seismic data from the Cheshire Basin and suggest as much as 850-900m of erosion into the underlying Wilmslow Sandstone Formation, an aspect discussed further below in Sections 6.4 and 9.4. It is, however, unclear from this discussion whether this supposed unconformity lies at the base of the previously defined Helsby Sandstone Formation, therefore the base of the Thurstaston Sandstone Member of that formation, or at the base of the predominantly fluvial Delamere Sandstone Member as suggested by Warrington *et al.* (1999).

The uppermost formations of the Sherwood Sandstone Group, the Helsby Sandstone Formation in the Cheshire Basin and the Ormskirk Sandstone Formation in the East Irish Sea Basin, vary from 128.00m (well 110/20-1) to 334.00m (well 112/25a-1) in thickness according to current definitions. These definitions are largely based on Thompson (1970a) and the identification of three lithostratigraphic units in the northwest parts of the Cheshire Basin; the Frodsham, Delamere and Thurstaston Members (Figure 1.2). In well sections the respectively mainly aeolian, fluvial and sandflat/aeolian members exhibit log signatures similar to those discussed above (well Knutsford-1). The largely aeolian Frodsham Member has a low gamma, low and rather erratic sonic; the fluvial Delamere Member has a high but spiky gamma and generally high but more uniform sonic; while the mixed sandflat and aeolian Thurstaston Member has a low base but locally erratic gamma and a low but also erratic sonic response. The wireline characteristics and their relationship to sedimentary facies have been tested against core derived facies (e.g. Meadows and Beach 1993a) and used to extend sedimentological interpretations beyond the limits of cored intervals (see also Section 6.2 below). In general it has been recognised that the measurably higher clay and diagenetic silica content of fluvial channel sandstones, compared to sandflat and aeolian sandstones, is responsible for significant differences in wireline log responses as well as porosity and permeability characteristics (Meadows and Beach 1993b). As applied in the Knutsford-1 well these criteria therefore define the base Helsby to top Wilmslow Sandstone Formations boundary as the change from erratic gamma and sonic responses above to a more uniformly low character in both logs below. Thompson (1970a) was concerned wholly with the subdivision of the Helsby Sandstone

Formation (then called the Keuper Sandstone) and did not define the base of the formation in any detail.

As discussed in Section 1.2, these lithostratigraphic units were carried into the East Irish Sea Basin and subsequently renamed as Members OS1, OS2a and OS2b from base to top with the same log based criteria being applied. Although the log characteristics for the three members have been used with some success, especially in the southern parts of the East Irish Sea Basin (e.g. well 110/13-1), the contact with the underlying Calder Member of the St Bees Sandstone Formation is significantly different. Instead of the uppermost Calder Member being defined by uniform gamma and sonic responses, in this area there is a distinctive unit with a high erratic gamma and high sonic velocity similar to that defining the Delamere and OS2a Members (e.g. wells 110/11-1, 110/12a-1,110/13-1). Where this boundary is cored (e.g. well 110/2-6) the OS1 Member is found to be largely aeolian and sandflat facies, while the uppermost part of the Calder Member is mainly fluvial channel sandstones.

Further north in the East Irish Sea Basin the problems of defining both the individual members and the base Ormskirk Sandstone Formation escalate significantly. In well 110/2-6 in the South Morecambe Field the base Ormskirk Sandstone Formation is picked on a prominent sonic log kick similar to that in wells to the S which coincides with the facies break mentioned above. The formation itself, however, more readily subdivides into two members, an upper erratic gamma, high uniform sonic and a lower low uniform gamma, low erratic sonic. In publications from British Gas, the former operators of the field, this well is divided into four members (Ebbern 1981), necessitating the need for four member names as discussed above in Section 1.2. Further N again, in wells 110/2b-9, 113/26-1 and 113/27-3 the identification of anything remotely resembling the criteria for the members becomes almost arbitrary. Intervals with log signatures similar to those described are present but do not lend themselves easily to a two, three or four fold subdivision. Likewise the base of the Ormskirk Sandstone, which is picked at one of several sonic velocity breaks with an upward decrease in well 110/2b-9 but at a gamma spike accompanied by an upward increase in sonic in well 113/26-1. Comments from British Gas personnel have indicated that the in-house 'rule of thumb' for defining the base Ormskirk Sandstone was to count down 800ft from the top of the Sherwood Sandstone

Group and then take the next decent gamma or sonic/density log pick (G. Cowan pers.comm.).

2.4 WELL CORRELATIONS

A variety of different surfaces have been used as a datum for well correlations in the Sherwood Sandstone Group including, most commonly, the supposed Hardegsen Unconformity at the base of the Ormskirk and Helsby Sandstone Formations (Colter and Barr 1975; Jackson *et al.* 1987; Jackson *et al.* 1997) and the top of the group at its contact with the overlying Mercia Mudstone Group (Jackson and Mulholland 1993; Yaliz 1997; Cowan and Bradney 1997). Alternatives that have been suggested include the base of the lowermost major claystone within the Mercia Mudstone Group for sequences within the Cheshire Basin (Mikkelsen and Floodpage (1997) and the top of the last major stacked fluvial channel sequence for wells in the East Irish Sea Basin (Thompson and Meadows 1997). These latter authors recognised the possibility that the contact between the Sherwood Sandstone Group and the Mercia Mudstone Group could be diachronous, first suggested by Fisher (1972), but lacked a verifiable datum from which to establish the nature and extent of the diachroneity.

Correlations based upon the base Helsby/Ormskirk supposed basal unconformity suffer from the difficulties inherent in attempts to both define this boundary and, even if satisfactorily defined from sedimentary facies, the problems of identifying the surface in uncored wells. For these reasons different authors have cited the same datum but generated different well correlations (compare Colter and Barr 1975 and Jackson *et al.* 1987). The majority of recent authors discussing well correlations or stratigraphy in the East Irish Sea Basin have used the top Sherwood Sandstone Group pick, while commonly acknowledging the potential diachroneity of the boundary (e.g. Cowan *et al.* 1999).

An example of the problems generated by unconstrained well correlations is provided by the four wells used in this study, 110/2-6, 110/8a-5, 110/13-5 and 110/14-3 which can be datumed on the top Sherwood Sandstone Group contact with the overlying Mercia Mudstone Group (Figure 2.1). These wells form a transect some 30 kms. long which passes from a near basin-margin position in the 110/14-3 well to the SE, basinwards to a near basin-centre position in the 110/2-6 well to the NW (Figure 2.2). All four wells are

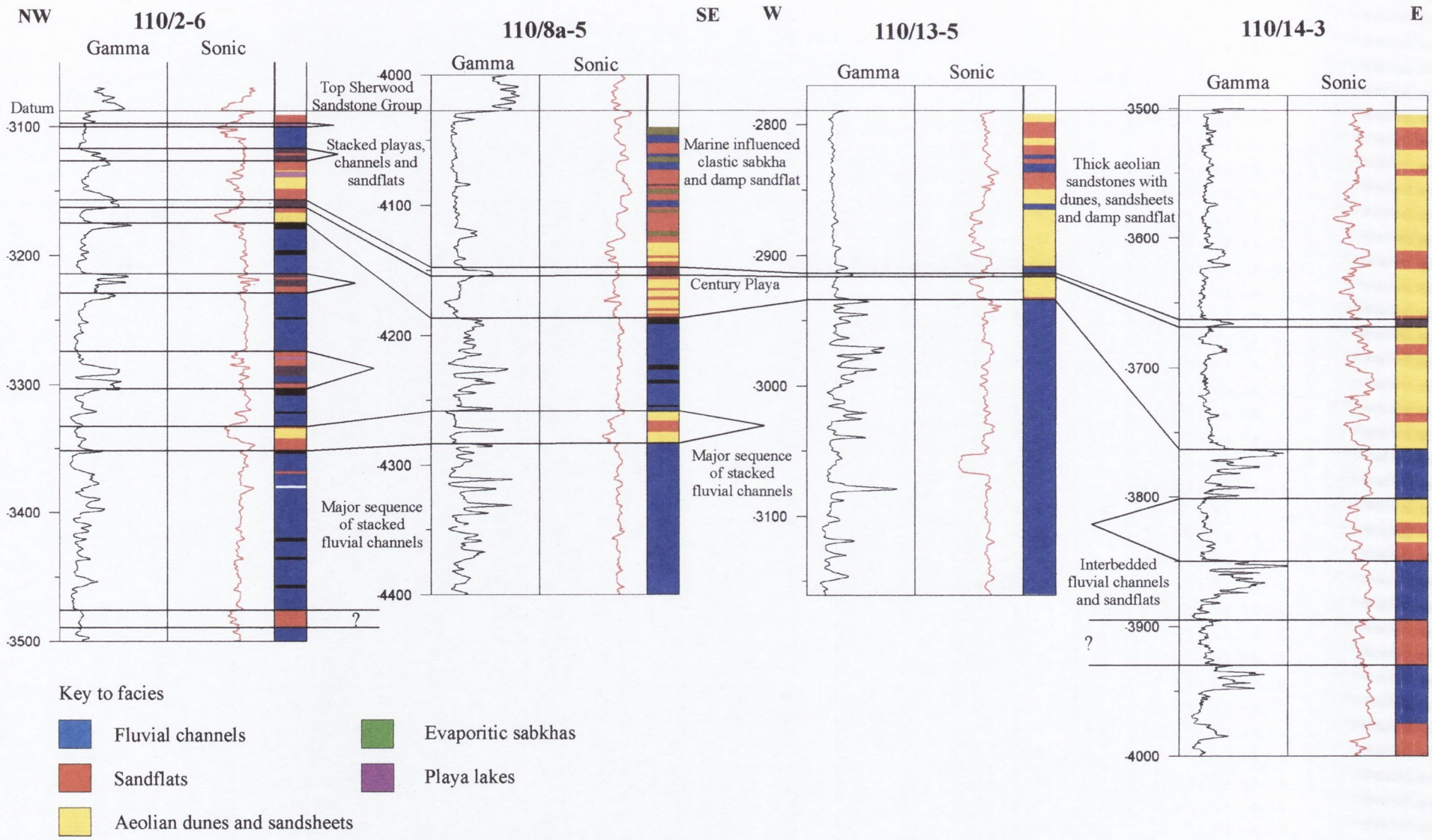


Figure 2.1 Well correlation based on top Sherwood Sandstone Group

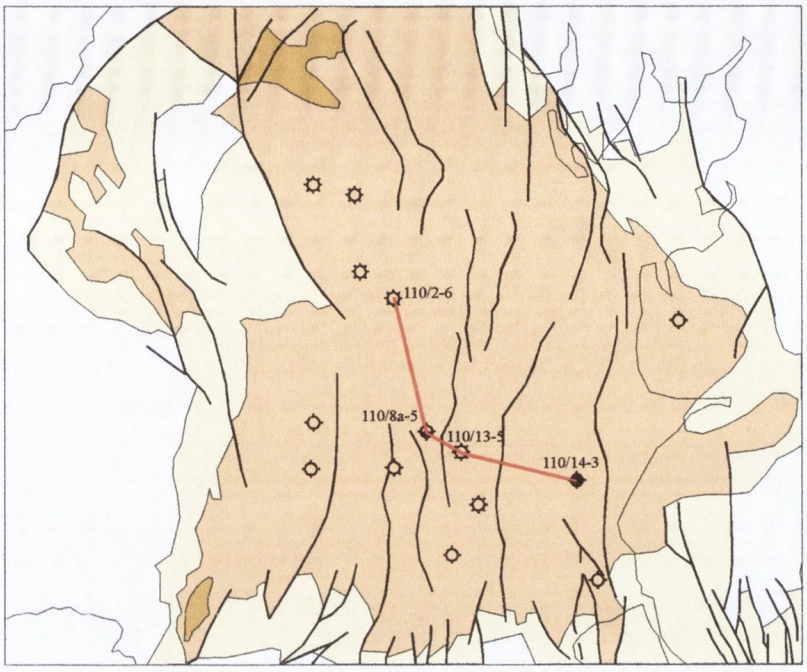


Figure 2.2
The East Irish Sea Basin with th location of the well section in Figure 2.1

extensively cored such that sedimentary facies have been defined (see Section 3 below) and, for two of the wells (110/8a-5 and 110/14-3) the interpretation of the facies has been carried into uncored intervals using the criteria cited by Meadows and Beach (1993a) and discussed above in Section 2.3. It is immediately obvious that there are significant sequences of stacked fluvial channel sandstones present in all four wells but that these occur at differing depths below the top Sherwood Sandstone datum. Correlation of the fluvial sequences leads to an apparent younging of the top fluvial channel correlation line from SE to NW and, hence, basinwards. Whilst not implausible, this does imply that major fluvial channels were still operating towards the basin centre at a time when they had ceased, to be replaced by sandflat and aeolian dune successions, around the basin margin.

The problems with this correlation are, however, compounded by the presence of a laterally extensive playa lake sequence that has also been suggested to be correlatable across the basin (see references in Section 3.4.1 to the 'Century Playa'). Within the present correlation this playa also appears to climb through the stratigraphy from basin margin to basin centre. Lastly, but somewhat more damaging to the viability of the top Sherwood Sandstone datum, is the presence in well 110/8a-5 of clastic sabkha sequences in the upper parts of the succession (described in Section 3.3.6). These sequences, in this

well, have been analysed and discussed at length by Greenwood and Habesch (1997) and Thompson and Meadows (1997) who show that the primary anhydrites that form an integral component of the clastic sabkha facies have an isotopic signature consistent with Early Triassic seawater as determined by Claypool *et al.* (1980). In this well correlation the marine influenced sabkhas therefore become the lateral equivalent, basinwards, of the fluvial channel, sandflat and aeolian sandstones in well 110/2-6 at an equivalent depth below the top Sherwood Sandstone datum and therefore presumably downslope. Clearly this method of well correlation has insurmountable problems and fails to provide a realistic impression of the lateral facies changes that are essential to an understanding of stratigraphic architecture. The problem remains, however, one of determining a viable and readily identifiable datum that provides an alternative correlation between these or any other wells.

3. SHERWOOD SANDSTONE GROUP SEDIMENTOLOGY

3.1 INTRODUCTION

During the course of the present study a total of 978.70m of core and outcrop within the Sherwood Sandstone Group has been sedimentologically logged, the latter in sections perpendicular to the dominant bedding and the 1:50 scale sedimentary logs generated are presented in Appendix II. The facies identified are described and interpreted below in terms of four major depositional environments comprising fluvial channel fills, sandflats (including aeolian dunes and sandsheets), floodplains (including playa lakes) and alluvial fans. Initially, these facies are discussed independent of the internal Sherwood Sandstone Group stratigraphy, this aspect being addressed later in Sections 6, 7 and 8.

Fluvial channel fills are sub-divided into six facies representing sub-environments broadly determined by variations in the flow regime within the channels. These are termed herein high stage bars and compound bars representing the highest flow stages, low stage bars and inter-bar channel deposits representing progressively lower stage flow and abandonment and partial abandonment deposits representing the lowest stages of flow to ponding and stagnation within channel anabranches. It is recognised that this hierarchy, especially in the distinction of the larger scale beds, presents a simplified model of fluvial deposition and that the individual cross stratified bedforms may represent component parts of larger in-channel bedforms as described by Bridge and Tye (2000). The differentiation of bedform scales is nonetheless considered justified in that it serves to illustrate both the variability of flow regime in the Sherwood Sandstone Group rivers and the heterogeneity of the channel fills that form an important part of the succession. Additionally, the use of the term 'bar' is preferred herein to that of 'dune' (*sensu* Jackson 1975) for bedforms of decimetre scale and above in accordance with standard practice in the published literature (e.g. Miall 1978; Bridge 1993; Bridge and Tye 2000).

The term sandflat is used herein to refer to the almost totally sand-dominated floodplains that may, and are suggested to, have formed lateral to and synchronous with the active fluvial channels. This extends the rather restricted usage of the term employed by, for example, Hubert and Hyde (1982) who recognise sandflats only as the terminal areas of alluvial fan systems. The term is, however, considered appropriate in the present case as it

serves to distinguish this important facies association from the volumetrically much less significant fine grained floodplain facies. Sandflats are also subdivided into a total of six facies, five of which represent variably wet to dry conditions on the depositional surface that were largely determined by the relationship between that surface and the palaeo-water table. These are termed wet sandflat, damp sandflat and dry sandflat and these together with aeolian sandsheets and aeolian dunes comprise a continuum of sandflat depositional environments. It is recognised that the boundaries between these sedimentary facies are necessarily arbitrary but the distinction is considered to be both valid and useful as it allows inferences regarding palaeo-climate and has significant implications in terms of the reservoir quality of the sandstones. The sixth sandflat facies is termed clastic sabkha and is used exclusively for sandstone dominated intervals with abundant evaporite cement (mainly anhydrite) and primary anhydrite laminae. Such intervals are recorded principally in the cores from well 110/8a-5 in the East Irish Sea Basin and are considered to be synonymous with the 'damp sabkha' facies of Herries and Cowan (1997).

Fine grained facies are referred to floodplains *per se* and are sub-divided into four facies comprising playa lakes, playa margins, sheetfloods and vegetated floodplains. Playa lake and related sequences are recorded mainly from the cored intervals of offshore wells where they form a locally significant component of the sedimentary succession in the uppermost parts of the Sherwood Sandstone Group. Within these successions playa lake and related deposits can be seen as a further part of the continuum of sandflat depositional environments, thus representing episodes during which the water table was temporarily above the sediment surface. These facies are rarely seen at outcrop in the Cheshire Basin but are recorded onshore in west Cumbria where they occur at the base of the Sherwood Sandstone Group at its junction with the underlying Barrowmouth Mudstone Formation (discussed further in Section 8.3). The use of the term playa lake, as applied herein, is consistent with the proposed definitions of Briere (2000) in that it implies 'an arid zone feature, transitional between a playa and a lake' that is therefore neither dominantly dry (playa) nor dominantly wet (lake). This therefore allows the possibility of extensive flooding but also allows for extended episodes with a negative water balance and the likelihood of surficial drying and desiccation.

Alluvial fan facies are positively identified only at Alberbury in the extreme south of the Cheshire Basin (see Figure 1.5) although, due to the paucity of outcrop, this section has not been sedimentologically logged. Potentially distal alluvial fan facies are recorded on Little Hilbre, one of the group of small islands lying offshore Wirral in the mouth of the Dee Estuary (visited but not logged during the course of this study).

3.2 FLUVIAL CHANNEL SANDSTONES

3.2.1 High stage bar sandstones

Intervals interpreted as the depositional products of high stage bars are recorded in all cores and outcrops where fluvial channels are present. They generally comprise metre scale cross stratified sets (Figures 3.1 and 3.2) of moderately or poorly sorted fine to medium, medium or coarse sandstone. Cross stratification can be tabular or asymptotically based onto planar erosive or scoured basal surfaces, while the sandstones can include a range of exotic clasts dominated by quartz but also including feldspars, metamorphosed sandstones and siltstones, volcanic fragments, chert and, rarely, fragments of limestone (see Section 4.2 below). The exotic clasts, where recorded, are mainly granule to medium pebble grade but rarely range up to small cobble grade and are either concentrated as a lag deposit at the base of a set or are scattered along foreset surfaces in a manner indicative of gravel overpassing as described by Allen (1983). The abundance and the size of exotic clasts, as with grain size generally in the fluvial sandstones of the Sherwood Sandstone Group, tends to decrease northwards from the Cheshire Basin into the East Irish Sea Basin with no granules or pebbles being recorded north of well 110/8a-5 (see Figure 1.5).

Intraclasts comprising claystones, siltstones and sandstones are incorporated within high stage bar sandstones more commonly than the exotic clasts and range from granule up to large cobble grade (Figure 3.3). In cored intervals it is not uncommon for such clasts to exceed the core diameter, rendering the determination of clast size somewhat inferential. The largest such intraclasts are recorded within the bases of channels where these are incised into sandflat or aeolian sandstones such as at Carden Park (c. 7.00-8.40m) and Helsby Hill (c. 40.00-41.00m). They can locally include sandstone blocks ranging from small cobble grade up to several 10's centimetres across (Figure 3.4).

Figure 3.1 High stage bar c. 2.00m in preserved thickness in the Chester Pebble Beds Formation at Bromborough Beach (11.20-13.20m on log)

Figure 3.2 Small rock stack in the Delamere Member of the Helsby Sandstone Formation at The Breck, Wallasey, with c.2.50m thick high stage bar (see camera bag for scale).

Figure 3.3
Intraclast rich high stage bar sandstones forming a high angle cross stratified set overlying a markedly erosive channel base cut into damp sandflat sandstone. Approximately 1058.10-1058.50m in well 110/2-6

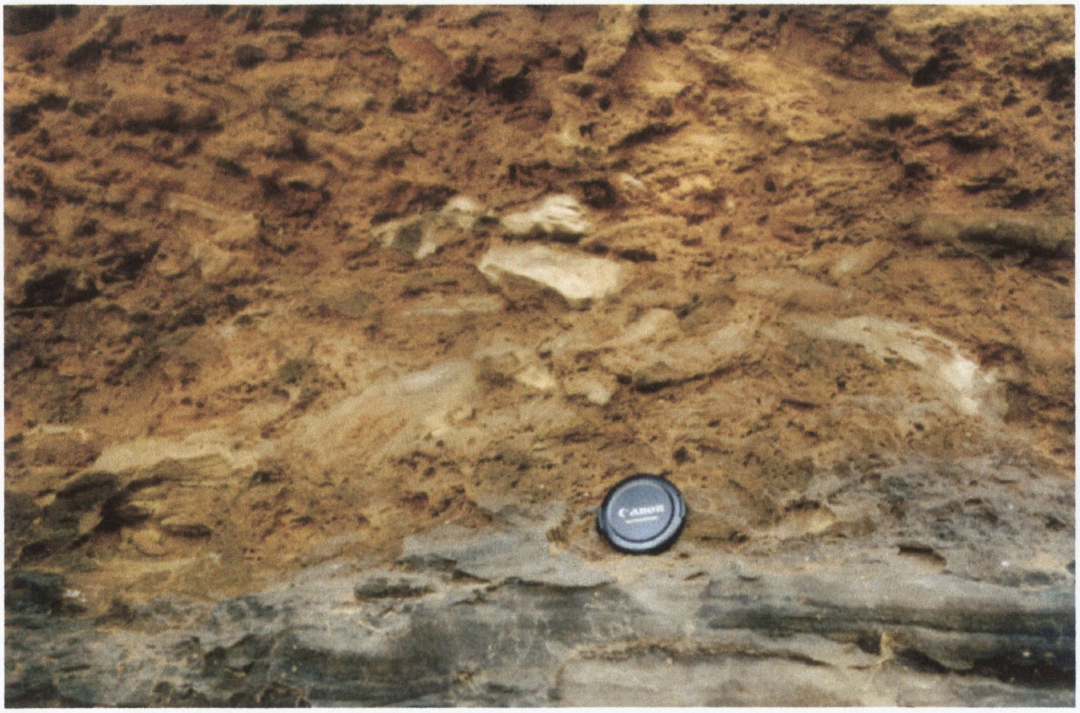


Figure 3.4 Incised erosive channel base overlain by sandstones with pebble to large cobble grade intraclasts of reworked fine to medium sandstone at Helsby Hill (40.00-41.00m on log)

Sandstones interpreted as high stage bars are suggested to represent the products of traction carpet processes within highly active channels at times when the water depth and flow competence were such as to allow the construction and migration of major bedforms. Although preserved high stage bar bedforms are commonly in the range 0.80-1.50 metres in thickness they range up to a maximum of approximately 2.50 metres (e.g. Burton Point, see log depths 53.40-55.95m). In this latter instance the bar appears to be preserved in its entirety with a complete succession of toesets, foresets and topsets evident in the outcrop, thereby providing a minimum estimate of water depth within the channel. Additionally, it is noticeable that, while an exotic assemblage of quartz, K-feldspar, volcanic and chert pebbles are scattered along the foreset surfaces, they are absent from both the toesets and the topsets, supporting inferences above regarding a gravel overpassing process. Soft sediment deformation is a common feature of these large barforms, mainly in the form of slumped foresets (Figure 3.5) that suggest partial collapse of the bar front, potentially due to the emergence of the bar top during falling stage thereby creating an inherent instability in the slipface.

In outcrops where the geometry of high stage bar sets can be observed they are commonly seen to be laterally extensive on a scale of 100's metres parallel to the apparent flow direction but are commonly wedge or trough shaped perpendicular to flow. Where high stage bars overlie a channel base this can also be seen, in favourable outcrop sections, to be trough shaped reflecting the scale and geometry of channel anabranches (Figure 3.6). It is notable that the dip direction of foresets within high stage bars is commonly highly oblique to the overall channel orientation where this can be observed, leading to apparently discordant orientations of foresets, especially where high stage bars with opposite polarities are juxtaposed (Figure 3.7).

This geometry is inferred to reflect the preservational nature of the in-channel bedform responsible and is determined by the downstream migration of the bar during episodes of peak discharge within a channel. Bridge (1993) describes flow around in-channel bars as similar to that in single-channel sinuous rivers such that flow around the curved margin of a bar results in a flow-transverse component of water surface slope towards the inner, convex, bank and generates a spiral flow pattern. The resultant modification of bar

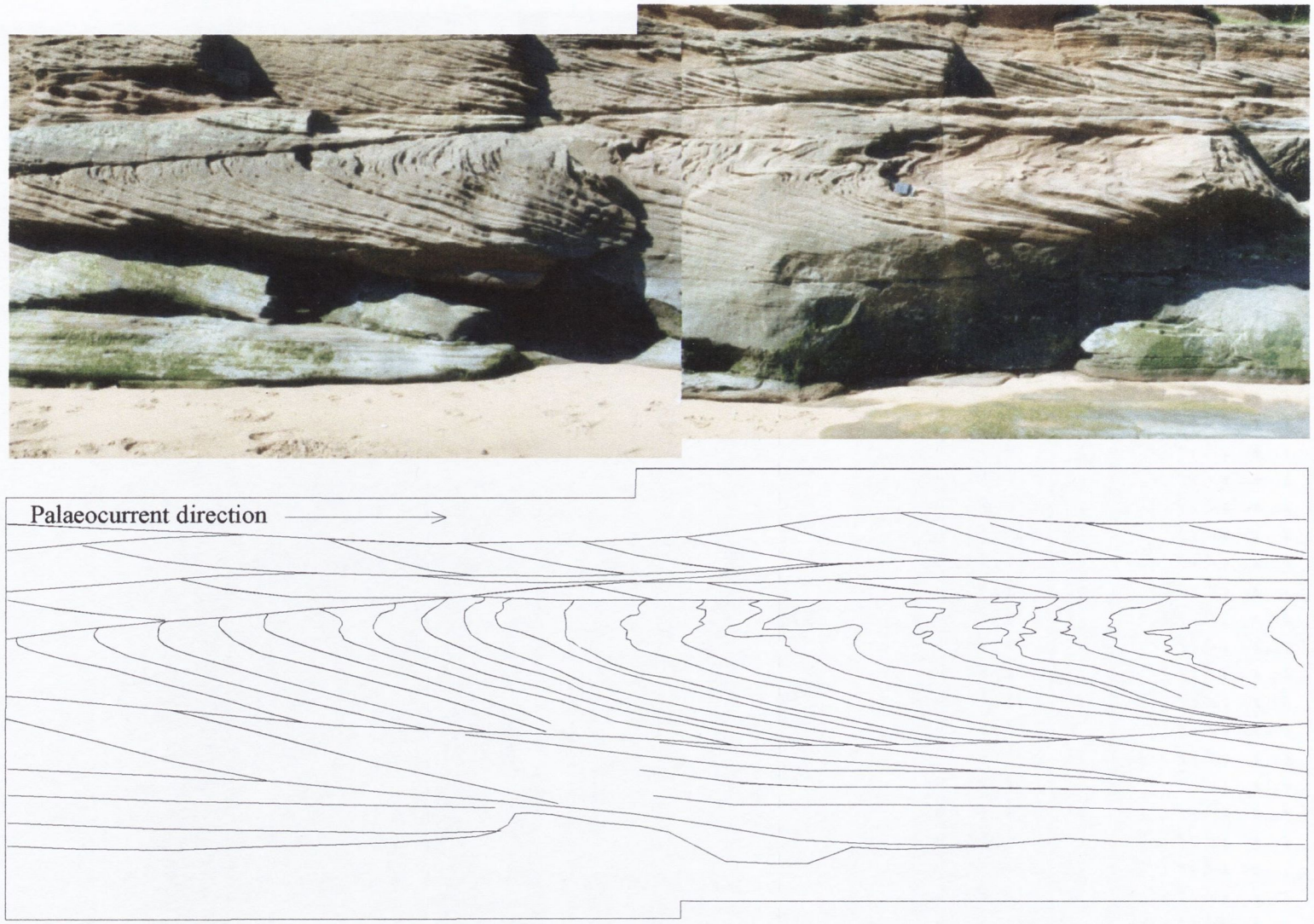


Figure 3.5 Slumped and overturned cross stratification within a high stage bar at Bromborough Beach, Wirral. The orientation of the collapsed foresets is obliquely right toward the viewer and hence becomes more intense in this directional (note the lens cap for scale in the centre right of the view).

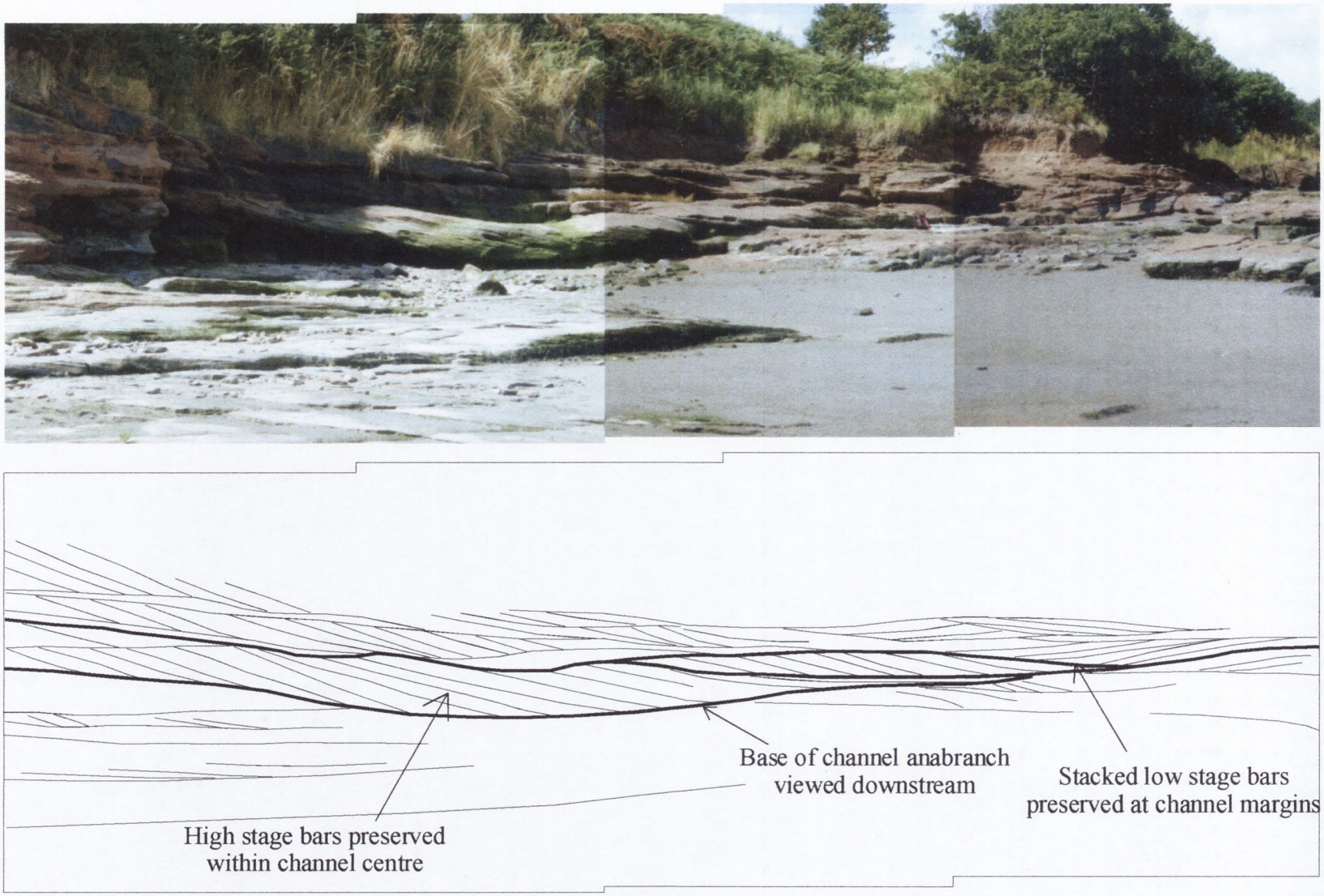


Figure 3.6 Cross stratified high stage bar sets viewed in a downstream direction at Bromborough Beach (note the rucksack for scale and the dip of cross stratification at nearly right angles to the channel orientation).

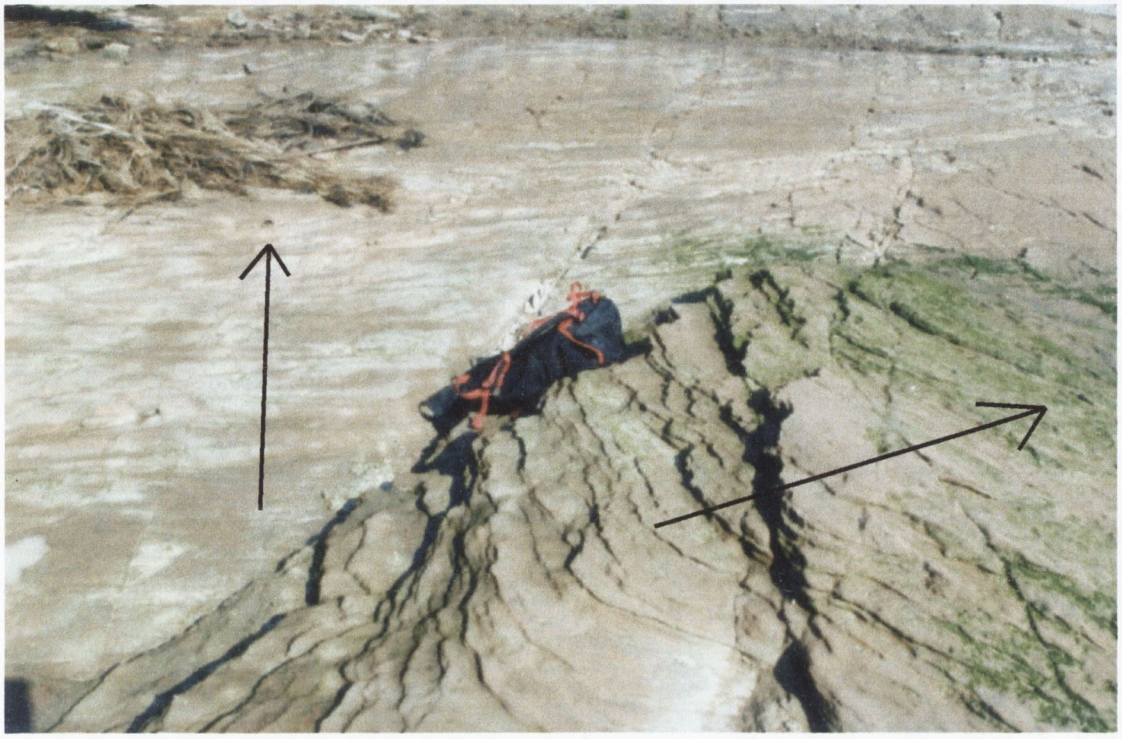


Figure 3.7 Superimposed high stage bars with opposing polarity (arrows show apparent palaeoflow directions from the orientation of foresets)

geometry during episodes of migration tends to produce an advancing avalanche face that becomes highly oblique to the overall channel orientation. This can be seen in modern braided rivers, both in general as seen in an aerial view of the Wiamakariri River in New Zealand (Figure 3.8) and in more detail from examination of a single large bedform preserved during the summer low stand in the River Loire in France (Figure 3.9). This property of large fluvial bedforms in low sinuosity systems can be used in appropriate ancient examples to determine the orientation of the channel axis as demonstrated by Long *et al.* (2001).

These large scale sets can occur singly, forming the whole of a channel fill (as in the example at Burton Point cited above), or as a component of a more complex channel fill in combination with other fluvial bedforms. An example of the latter is provided by outcrops at Bromborough Beach (Figure 3.10 and log depths 48.30-52.60m) where an individual channel fill comprises a highly heterogeneous association including a high stage bar, dune scale bedforms interpreted as low stage bars and very low angle to flat lamination interpreted as inter-bar channel deposits overlain by thin cross stratified beds potentially representing partial abandonment. Alternatively, high stage bars can occur as a stacked

Figure 3.8 The Wiamakariri River in South Island, New Zealand, showing bar geometries and the relative orientation of active bar fronts in a low sinuosity braided river.

Figure 3.9 High stage bar exposed at low stage in the River Loire near Saumur (the crest of the avalanche face of the bar is highlighted and is highly oblique to the channel orientation in this downstream view)

Figure 3.10 A sandstone sequence of various bedform scales comprising a high stage bar, low stage bars and inter-bar channel sandstones illustrating the range of flow regimes and/or water depths recorded within a single channel fill at Bromborough Beach.

sequence within a single channel fill, commonly with inclined set boundaries, where two or more such large scale bedforms are amalgamated within a single channel. In a number of instances high stage bar bedforms form the lower part of a sequence of bedforms with upward decreasing preserved set thickness that can be interpreted as representing waning flow conditions during deposition (e.g. Burton Point, log depths 41.70-44.50m). It is, however, not uncommon to find the reverse situation with low stage bedforms, mainly flat lamination, overlying a channel base with an upward increasing scale of dunes and bars forming the remainder of the channel fill (Figure 3.11) suggesting rising flood conditions during deposition (e.g. Hilbre Point Offshore, log depths 3.25-5.60m, and St Bees South Head, log depths 82.40-86.35m). Conversely, there are also examples of single channel fills exhibiting preserved bedforms representing initially rising flood conditions culminating in a high stage bar followed by waning with both bedform scale and, in some instances, grain size increasing and then decreasing upwards through the sequence (e.g. St Bees South Head, log depths 100.95-103.55m).

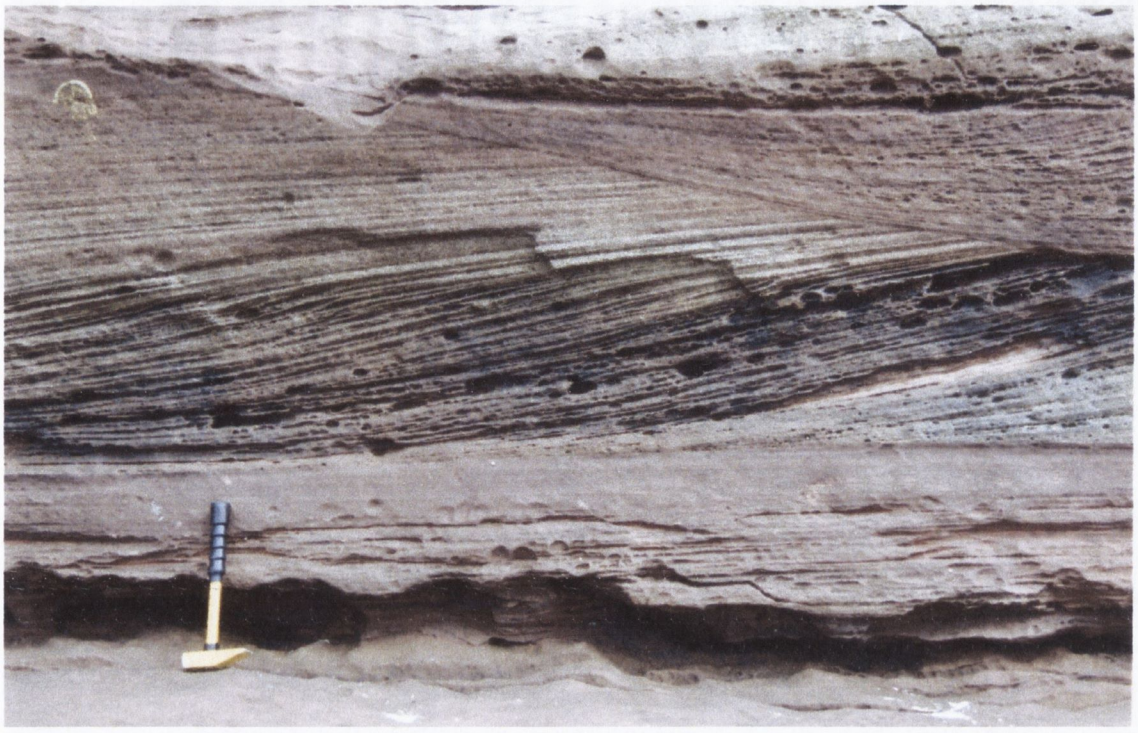


Figure 3.11 Flat laminated sandstones overlying a channel base and in turn overlain by cross stratified sandstones forming bar bedforms in a rising flood sequence at St Bees South Head, west Cumbria

3.2.2 Compound bar sandstones

A number of large in-channel bedforms preserve an internal structure indicative of progressive development in the form of intrasets (*sensu* Collinson 1968), comprising small scale downclimbing sets developed within the foresets of large bar bedforms, and stacked amalgamated decimetre scale sets that are clearly component parts of a larger structure when viewed in outcrop (Figure 3.12). The former are recorded mainly in cores from offshore wells, notably well 110/2-6 (e.g. 1021.50-1025.25m), and the latter can be seen in the logged section at Beeston Castle (log depth 3.00-7.20m). It is considered possible that certain cored intervals may include channel filling sequences similar to that observed at Beeston Castle but the limitations of core make such interpretations difficult without the advantage of bar geometry that outcrop affords.

These large scale channel bedforms are similar in sandstone composition to the high stage bars described above although the decimetre scale component bedforms seen in outcrop tend to be somewhat sparse in both exotic and intraformational clasts. Where intrasets are present they dip predominantly in the same direction as the foreset surfaces that bound

Figure 3.12 Compound bar overlying a markedly erosive channel base (highlighted in yellow) and almost flat top (highlighted in red), also exhibiting internal heterogeneity in the form of dune-scale subsidiary bedforms and minor syn-depositional scours (Beeston Castle Inner Ditch, Cheshire)..

them, thus precluding their potential interpretation as point bars. Where recorded in the cored interval from well 110/2-6 the compound bars range between 3.30m and 3.80m in preserved thickness, while that at Beeston Castle is 4.20m in preserved thickness. In each instance the compound bar forms all, or the vast majority, of an individual channel filling sequence.

These sandstones are interpreted as the preserved depositional products of major in-channel bedforms or side-attached bars, the latter being in accordance with interpretations of similar structures in the Upper Carboniferous of northern England by McCabe (1977). As with comments above concerning high stage bars, such bedforms would have formed and migrated only at times of peak discharge and bank-full conditions. As commented by McCabe (1977) it seems unlikely that such bars would form with crests normal to the palaeo-flow direction as this would require an extremely high coarse sand suspended sediment load and a high ratio of depth of water over the crest to depth of water in the bedform trough. It is more probable that the bedform crest was oblique to the channel

orientation, allowing reworking of slipface sediment and the generation of the subsidiary bedforms responsible for the intrasets as the bar migrated downstream and across the channel thalweg. This implies a more steady state high stage flow within the channel, allowing time for bar development, migration and the formation of intrasets, an inference that has implications for any consideration of overall flow regime (discussed below in Section 3.6).

3.2.3 Low stage bar sandstones

Decimetre scale bedforms comprise the most abundant facies forming a component of the fluvial channel fills and are recorded within all logged intervals representing fluvial channels. They generally comprise moderate to well sorted fine and medium sandstones, mainly devoid of exotic clasts but commonly including a sparse assemblage of claystone and/or siltstone intraclasts. Sets range from less than 10cm to c.80cm in preserved thickness but are generally in the range 40-60cm and commonly exhibit moderate to low angle or trough cross stratification (Figure 3.13) with either tabular or asymptotically based foresets overlying planar erosive bases. In the majority of instances these sets are stacked, being both laterally and vertically amalgamated and are often associated with other fluvial bedforms to form compound channel filling sequences.

These intermediate scale bedforms are interpreted as representing traction carpet sedimentation within active fluvial channels in locations or at times when flow competence and/or water depths were adequate for the transportation of sand grade material but insufficient to generate the larger bedforms discussed above. Potentially this may occur within channel anabranches that are subsidiary to the main flow or within a major channel at times of reduced flow. Although examples of both these possibilities are almost certainly present in the Sherwood Sandstone, the common occurrence of stacked and amalgamated channel fills dominated by low stage bars (e.g. well 110/2-6, log depths 968.10-973.10m and 992.50-997.15m) suggests that temporal rather than spatial parameters were at times the more important.

In outcrops the low stage bars are generally of limited lateral extent, both parallel and transverse to apparent palaeoflow directions. In favourable exposures where a datum to a channel base can be established, some bars exhibit a climbing geometry (Figure 3.14) with

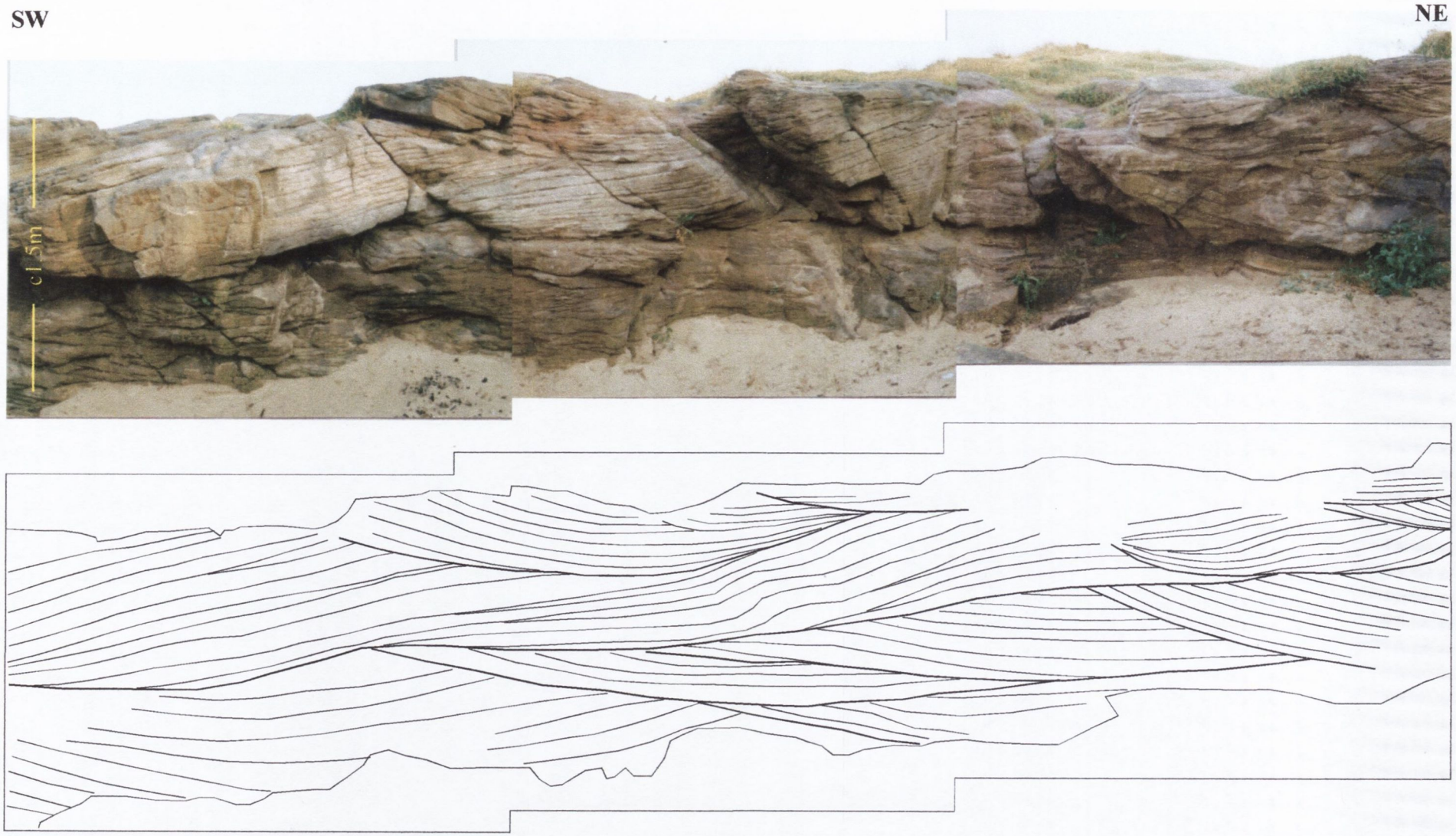


Figure 3.13 Transverse view through a series of stacked trough cross stratified low stage bars forming part of a channel filling sequence at Hilbre Point (part of succession shown at log depths 3.00-7.00m on 1:50 sedimentary log for Hilbre Point South)

set bounding surfaces seen to be dipping in the upstream direction at shallow angles such that they may represent the upstream parts of larger bar bedforms (*sensu* Bridge and Tye 2000). In such cases the bedforms tend to evolve in the downstream direction, becoming smaller and breaking down into component ripple or dune scale structures and, in some instances, into parallel lamination. This dissipation of the low stage bars is assumed to reflect their migration into shallower water depths as they effectively become parasitic bedforms on the margins of larger in-channel structures, represented by the high stage and compound bars discussed above. In such cases, it is assumed that the major bars are effectively stationary, and potentially may be partially exposed, such that the channel anabranches in which the low stage bars are developed and migrate are forced to divert around the major bedforms imparting a sinuosity to the anabranches greater than that of the channel system as a whole. It is noticeable from the outcrop logs where apparent palaeoflow directions can be measured that low stage bars within the same sequence can display a wide range of cross stratification azimuths (e.g. Fleswick Bay, log depths 3.05-6.40m), a variability that may, in part at least, reflect the sinuosity of the channel anabranches in which they were deposited.

3.2.4 Inter-bar channel sandstones

Intervals of flat lamination or very low angle cross stratification recorded within channel filling sequences occur interbedded with a range of bar bedforms and are interpreted herein as representing deposition at the lowest stages of active flow within shallow channel anabranches diverted around the major bedforms.

The sandstones forming these intervals, which range from a few centimetres to more than a metre in preserved thickness, are generally moderate to well sorted and fine to medium sand grade. Exotic granules and pebbles, together with claystone or siltstone intraclasts are rare and, where present, are preserved as a sparse basal lag. Sedimentary structures are dominated by a finely developed lamination which, where a bedding surface can be examined, sometimes exhibits primary current lineation. In core these intervals are most commonly logged as flat lamination as the nature of core precludes observation of the lateral geometry of bedforms. In larger outcrops, however, it becomes possible to observe that in many cases this lamination represents the preserved stoss slope and topsets of very

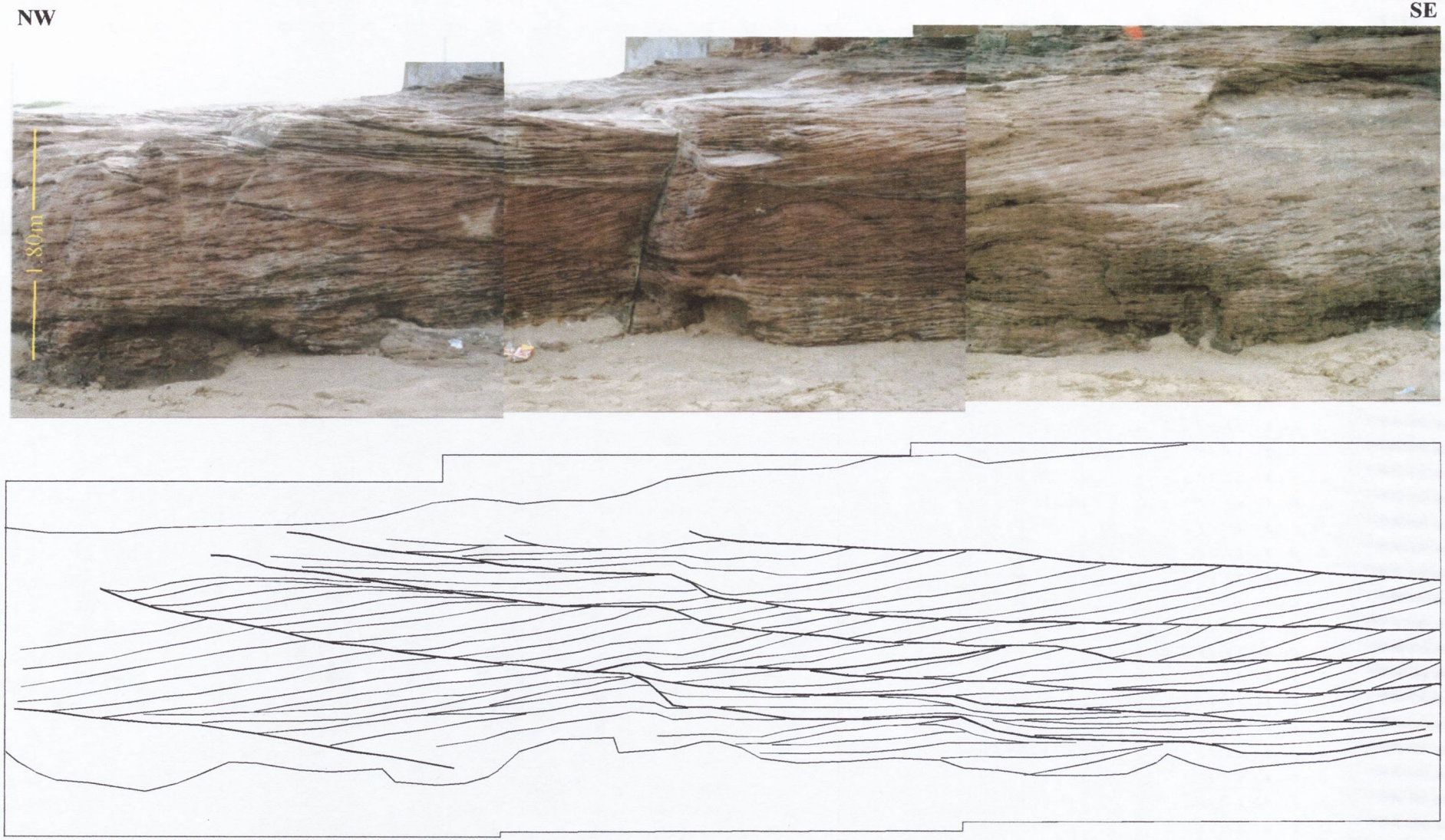


Figure 3.14 Longitudinal view showing climbing geometries within stacked low stage bars at Hilbre Point (succession shown is at log depths 0.00-1.80m on the 1:50 sedimentary log for Hilbre Point north). Palaeoflow direction to the left.

low relief bedforms (Figure 3.15) that, with an amplitude of 0.5m or less, may be traced for many 10's metres in the downstream direction. Intervals of genuine flat lamination are also recorded, although these too commonly preserve primary current lineation suggesting upper rather than lower flow regime conditions.

Flat lamination and very low angle cross stratification has been previously recorded in several modern sandy braided river systems, most notably in the Brahmaputra where it demonstrably relates to bar-top environments and is interpreted as being generated in response to shallow water high velocity flows across bars during falling stage (Bristow 1993). In the present case intervals of bar-top reworked sandstones are undoubtedly present (e.g. well 110/2-6, log depths 1031.30-1032.40m) but represent a small proportion of the total preserved intervals of flat to very low angle lamination. It is noticeable in outcrops that preserved intervals dominated by this type of structure are most common as distinct sequences in the base of compound channel fills, where these can be observed, that can also include both high and low stage barforms. It seems likely, therefore, that the preservational potential of bar-top flat lamination is relatively low; these would be the first sediments to be reworked during any subsequent flood following the falling stage modification of a bar-top. By comparison, flat to very low angle lamination deposited directly above a channel base would be most likely to be preserved in any subsequent flood that did not scour the entire channel.

The circumstances in which flat lamination or very low relief bedforms might be generated in an active channel include, notably, the conditions at which the lowest stage of flow pertains within a channel. At this stage any flow would be diverted around the major bedforms, these having been effectively frozen by falling water levels, such that the channel system would devolve into a network of anabranches. At the lowest stage necessary to maintain flow within these channels water would tend to pond behind the major bars and form a pool and riffle system comprising a series of near stagnant pools connected by shallow but fast flowing rapids or riffles (Figure 3.16). Bedforms generated within these riffles are likely to be low relief and dominated by upper phase structures, to directly overlie the channel base and, during any subsequent flood, to be over-run and potentially preserved beneath migrating bar bedforms. Unless demonstrably formed

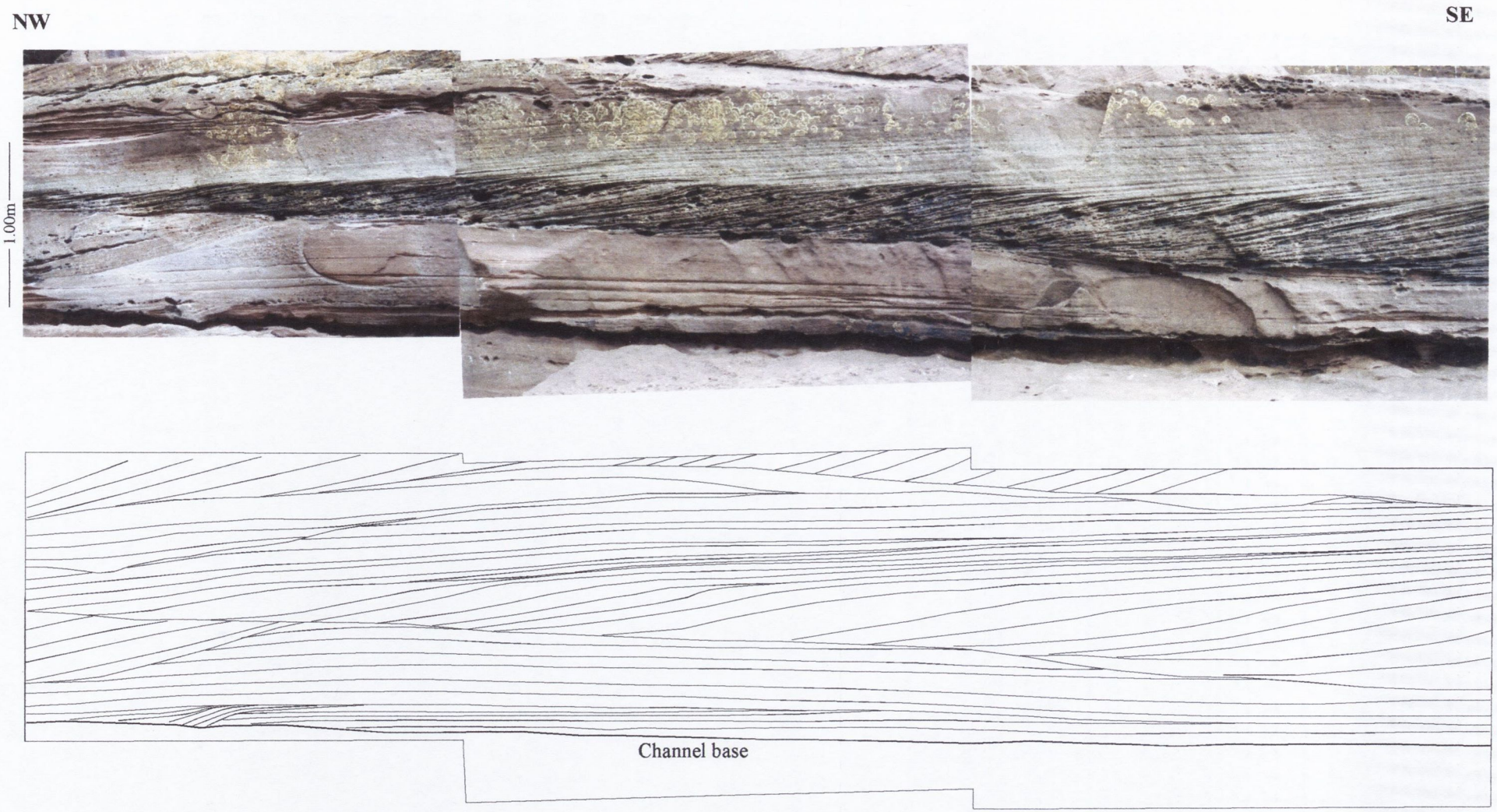


Figure 3.15 Flat laminated to very low angle cross stratified sandstones forming the basal succession within a fluvial channel fill at Fleswick Bay, west Cumbria. Low angle discordances separate very low relief bedforms without discernible slipfaces

Figure 3.16 A reach of the River Loire near Saumur, France, at low stage showing flow diversion around the major bars and the development of anabranches comprising a pool and riffle system with partial stagnation in the pools and flow acceleration through riffles

during bar-top reworking, intervals of flat laminated or very low angle cross stratified sandstones are therefore interpreted herein as representing deposition at low stage within channel anabranches formed between the major bars.

3.2.5 Abandonment sandstones, siltstones and claystones

Generally thin intervals of claystones, siltstones and very fine to fine sandstones associated with the sandy channel filling bedforms described above are interpreted as suspension fines, windblown detritus and minor sheetfloods deposited within standing water bodies formed as a result of channel abandonment. The majority of the recorded abandonment sequences occur in the cored intervals of the offshore East Irish Sea Basin wells and very few such sequences are seen at outcrop. Whether this reflects a greater abundance of preserved abandonment intervals in the offshore areas of the East Irish Sea Basin or just a predisposition of outcrops towards the more resistant channel filling sandstones is unclear. Intervals interpreted as representing the abandonment of fluvial channels are dominated by flat laminated or blocky red or grey claystones and siltstones with interlaminated very fine

to fine sandstones (Figure 3.17). The sandstones generally form beds less than 10cm in preserved thickness and can be flat laminated, current rippled or, more rarely, wave rippled (e.g. well 110/13-5, log depths 938.80-939.30m). Soft sediment deformation is common, usually in the form of loaded bases to sandstone beds and water escape structures (e.g. well 110/8a-5, log depths 1287.10-1287.90m), while bioturbation is also recorded within many of the abandonment intervals, generally in the form of small sand-filled sub-horizontal burrows akin to the marine ichnogenera *Planolites*. Although generally sparse, in a few instances the bioturbation is so intense that much of the primary depositional fabric has been overprinted such that the sandstones exhibit a churned appearance (e.g. well 110/8a-5, log depths 1276.25-1277.55m).

The interpretation of these sequences as abandonment fines relies to some extent on their immediate relationship with underlying channel sandstones as their sedimentary characteristics are very similar to those of playa lakes (see discussion below in Section 3.4.1). The presence of laminated claystones and siltstones indicates extremely low energy levels and it is likely that the majority of the silt and clay grade material was deposited from suspension following either fluvial transport into a ponded area or entrapment by the

Figure 3.17
Abandonment claystones and siltstones overlying channel sandstones at Helsby Hill, Cheshire.

water surface of windblown dust. The current rippled fine and very fine sandstones represent traction carpet processes but these are likely to have been relatively low energy flows resulting from temporarily renewed minor flows within the abandoned channel or redeposition of sand grade material from adjacent bars as their margins collapse during emergence due to falling water levels.

3.2.6 Partial abandonment sandstones, siltstones and claystones

Intervals essentially similar in character to those described above as abandonment deposits but with a dominance of sandstone over siltstone and claystone are referred to partial abandonment conditions. As with abandonment deposits, these intervals are more commonly recorded in the cores of the offshore East Irish Sea Basin wells than in onshore outcrops.

The sandstones representing partial abandonment within fluvial channels tend to be moderately to well sorted very fine to fine and rarely medium sandstones exhibiting a range of sedimentary structures including flat lamination (Figure 3.18), current rippling and wave rippling (e.g. well 110/2-6, log depths 1006.20-1007.50m). They can be locally micaceous and rarely preserve primary current lineation suggesting temporary flow competences greater than those typical of the abandonment deposits. Soft sediment deformation and bioturbation (e.g. well 110/2-6, log depth 1038.60m) occur but are less common than those recorded within abandonment fines. Claystones and siltstones, where present, are less thickly developed and generally occur as thin partings and drapes overlying current ripples and wave ripples (e.g. well 110/13-5, log depths 905.85-906.50m). Where partial abandonment intervals are recorded within onshore outcrops, especially those in the Cheshire Basin where grains sizes tend to be somewhat greater than in the East Irish Sea Basin, they locally include fine to medium and medium sandstones forming small trough cross stratified sets (e.g. Bromborough Beach, log depths 16.50-16.95m).

The interpretation of these intervals as representing the partial abandonment of fluvial channels implies a transition between low stage bedforms such as dunes and inter-bar channel related lamination and true abandonment deposits. Additionally, their presence within channel filling sequences indicates the range of flow competences from high stage

Figure 3.18 Flat laminated locally silty fine sandstones (outlined in yellow) representing partial abandonment of a fluvial channel overlying metre scale cross stratified high stage bar sandstones at St Bees South Head, west Cumbria

bars to current ripples that can be generated by the fluvial system responsible for the Sherwood Sandstone Group fluvial sequences. Although partial abandonment deposits may in some instances represent merely an intermediate stage in the waning flow cycle within a channel anabranch, there is also the possibility that many such sequences represent the lateral, pool related, equivalent of the higher energy regime inter-bar channel deposits. In such a scenario, a low stage channel that had devolved into a pool and riffle system could be represented by upper phase plane bed lamination in the riffle areas and by clay draped current or wave ripples associated with near stagnation in the pool areas.

3.3 SANDFLAT SANDSTONES

3.3.1 Wet sandflat sandstones and siltstones

Within the continuum of sandflat and playa lake environments, sequences attributed to wet sandflats are akin to playa margin deposits (see Section 3.4.2) and only distinguished from these by their somewhat more sand-prone lithology and greater abundance of sandstone laminae suggestive of sub-aerial exposure (see discussion below). Wet sandflat deposits are recorded in most of the offshore wells, notably wells 110/2-6 and 110/13-5 in the more

central areas of the East Irish Sea Basin, but are rare in the Cheshire Basin, being recorded within the present study only in the Kinnerton Sandstone Formation at Burton Point (Figure 3.19).

Sequences interpreted as representing wet sandflats typically comprise moderate to poorly sorted silty or argillaceous very fine and fine sandstones exhibiting flat or irregular lamination that are commonly disrupted by bioturbation including *Planolites*- and *Thalassinoides*-type burrows (e.g. well 110/13-5; log depths 886.30-887.55m). Thin cross stratified sets, locally with small claystone or siltstone intraclasts at the base, are also present suggesting episodic traction carpet sedimentation, while wave ripples, locally modifying rare current ripples (e.g. well 110/2-6; log depth 950.10), indicate episodes of standing water conditions at the sediment surface. In the latter instance, the sandstone laminae tend to be draped by thin silty partings, potentially indicating the deposition of suspension fines.

The characteristics of wet sandflat sequences suggests a highly sand-prone environment with little topographic relief on which depositional processes were largely controlled by

Figure 3.19 Typical wet sandflat facies comprising finely flat and irregularly laminated silty sandstones exposed directly beneath the overhang of coarse fluvial sandstones and above the red aeolian dune sandstones at Burton Point, Wirral.

the relationship between the sediment surface and the palaeo-water table Some of the irregular laminations are likely to represent adhesion processes similar to those discussed below in Section 3.3.2 that require a damp substrate, while evidence for standing water in the form of wave ripples and wave modified current ripples suggests temporary ponding of the sandflat surface. The distinction between these sequences and those related below to a playa margin environment is, however, significant as the latter relate to the establishment of areally extensive if shallow playas, while the wet sandflat deposits are suggested to represent local ponding. Given that the range of sandflat depositional environments (discussed below) can be associated with subtle changes in the relationship between the palaeo-sediment surface and the palaeo-water table, wet sandflats represent the wettest end of that continuum with the water table either coincident with or above the sediment surface for the majority of depositional time.

3.3.2 Damp sandflat sandstones and siltstones

Sandstone dominated intervals ascribed to a damp sandflat environment occur in all cored intervals and are represented in all outcrops logged for this study that include sandflat facies. Damp sandflats, as defined herein, are synonymous with the sheetflood facies of Meadows and Beach (1993) and Thompson and Meadows (1997), some of the sequences ascribed to their aeolian dominated sabkha association by Herries and Cowan (1997) although the latter extend this association to include aeolian dunes and sandsheets that are described separately below and to the interdune facies of Mountney and Thompson (2002). The variety in the facies terminology applied to these sequences reflects both their inherent variability and changing views on their interpretation through time.

Damp sandflats comprise fine to medium sandstone dominated intervals in which the primary sedimentary structure is a wavy or irregular flat lamination interbedded on a millimetre to centimetre scale with finely flat laminated and commonly bimodally sorted sandstones and on a centimetre scale with current and wave ripple cross laminated sandstones (Figure 3.20). Cross stratified sandstone sets of decimetre scale occur interbedded with the damp sandflat sandstones described here, but these are discussed separately under a sheetflood heading below (see Section 3.4.3). In places, discontinuous lenses of sandstone up to several centimetres across, that are generally slightly more coarse than their host, are enclosed within the irregularly laminated intervals (Figure 3.21). Silty

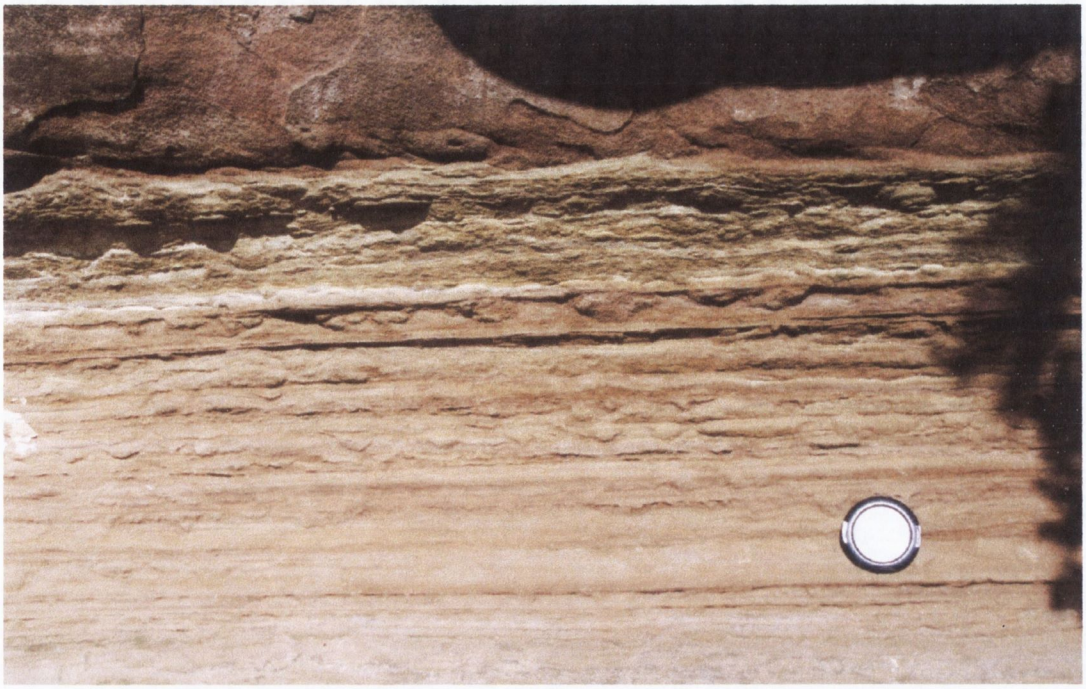


Figure 3.20 Irregularly flat laminated damp sandflat sandstones with evidence of current and wave rippling, load structures and bioturbation at Burton Point Wirral.

drapes and partings are common, both interlaminated with the wavy to irregular laminae and as form concordant drapes overlying ripples. Soft sediment deformation is ubiquitous and can take the form of small scale load structures (Figure 3.22), modification of ripple forms and bioturbation.

Of the bioturbation fabrics recorded, by far the most common are 0.2-0.4cm diameter sand-filled sub-horizontal burrows although larger 0.5-1.0cm sand-filled burrows are also present. These burrows are similar in form and morphology to the ichnogenera *Planolites* and *Thalassinoides* of shallow marine environments although it is rare that the branching networks of classic *Thalassinoides* are observed in the Sherwood Sandstone. In the almost entirely continental environment of the Early Triassic East Irish Sea and Cheshire Basins it is likely that the organisms responsible were small annelids and fresh water crustaceans. Additionally to these there are also sparse occurrences of similarly sand-filled sub-vertical burrows (e.g. well 110/2-6, log depth 1072.40m) and possible vertebrate footprints (e.g. Thurstaston Road Cutting, log depth 16.35m and Figure 3.23) similar to some of those

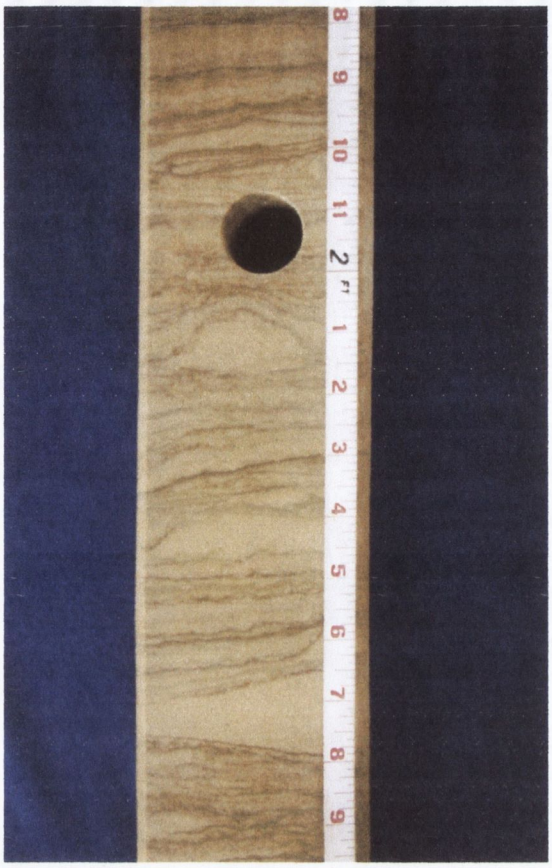


Figure 3.21
Damp sandflat sandstones with thin silty drapes and partings on discontinuous lenses and irregular laminae of medium to coarse and fine to medium sandstone. Well 110/2-6, core depths 1067.50-1068.00 m

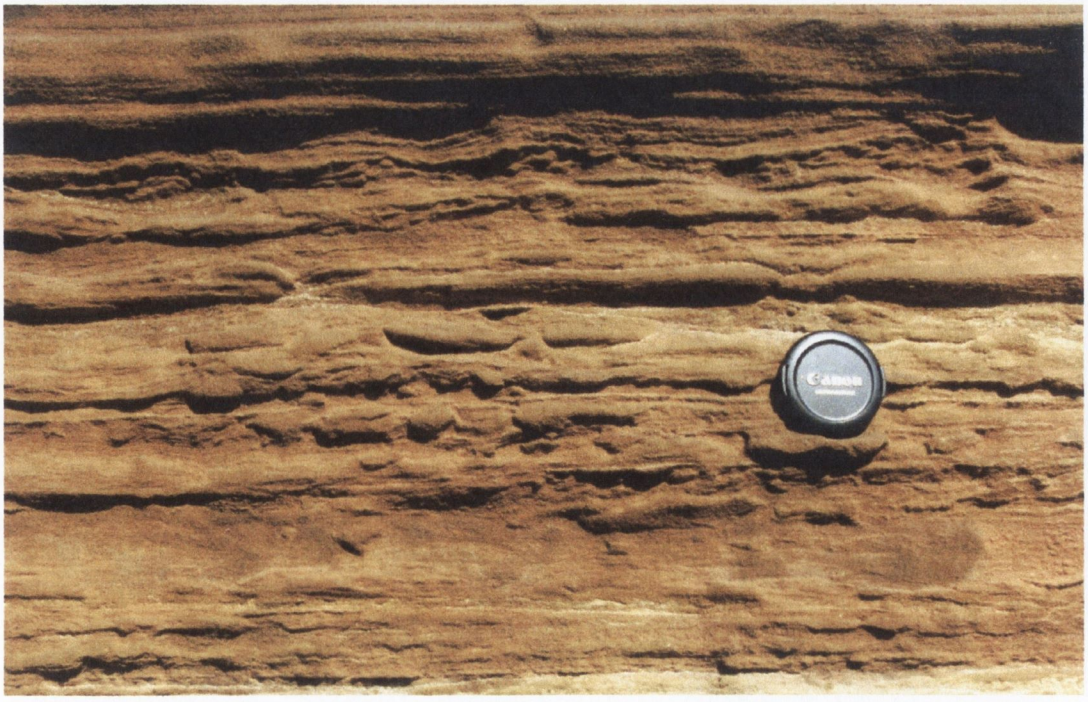


Figure 3.22 Finely laminated damp sandflat sandstones with common evidence of loading at the base of laminae, passing up into wind rippled aeolian sandsheet. Thurstaston Road Cutting, logged depth 13.00-13.50 m.

Figure 3.23 Vertebrate footprint approximately 10 cms. across preserved within damp sandflat sandstones at Thurstaston Road Cutting (logged depth c. 16.30 m.)

described from the Sherwood Sandstone at Hilbre Island by King and Thompson (2000). Unlike these latter, however, those at Thurstaston Road Cutting can only be seen in vertical outcrop where they form sand-filled shallow depressions up to 14cm across and around 6cm deep in which the fill can be seen to be massive in the base and, above this, is draped across the depression. From a size consideration alone, the indents at Thurstaston compare most closely with those identified as *Chirotherium* footprints by King and Thompson (2000).

The wide range of sedimentary structures encompassed within the damp sandflat facies in part explains the variety of environmental interpretations that have been placed upon these sequences but also reflects the range of processes that were responsible for their generation. It is clear that, as with the wet sandflat facies discussed above, the close proximity of the sediment surface and the palaeo-water table during deposition has played a significant role in their sedimentary character. Where the two were coincident it is likely that wind blown detritus (mainly fine sand in this sand dominated environment) would have adhered to the damp substrate to form adhesion ripples and it is also possible that irregular surfaces due to weakly preferential cementation of the surface by evaporitic

cements could have trapped wind blown sand in the manner described by Herries and Cowan (1997). In this situation it would require only a minor rise in the water table to generate ponding at the surface with the consequent formation of wave ripples and silty drapes from suspended sediment. Conversely, any slight fall in the relative water table would induce drying of the surface and the possibility that aeolian processes could be initiated. In favourable examples the finely flat laminated sandstones that form an inherent part of the facies preserve thin upward coarsening profiles indicative of wind ripples (*sensu* Hunter 1977), while elsewhere these thin interbeds preserve pinstripe lamination that is also recognised as resulting from the passage, but incomplete preservation, of wind ripples (Fryberger and Schenk 1988).

The depositional environment of the damp sandflat sequences would therefore appear to be, as with the wet sandflat facies, a sand-dominated area of little topographical relief subject to a permanently high water table that fluctuated in its relationship with the sediment surface. At times, and in places, where the water table rose temporarily above the sediment surface, deposition was controlled by shallow sub-aqueous processes including wind blown wave ripples and the suspension fall-out of wind blown fines. As the water table fell adhesion processes would have become dominant, together with disruption of the sediment surface in response to surficial precipitation of evaporite cements. These latter seem to have been the most significant processes accounting for the majority of the facies. With a further fall in the relative water table, surficial wind reworking would have generated the typical pinstripe lamination that forms a minor but significant component of the damp sandflat facies.

3.3.3 Dry sandflat sandstones

Intervals ascribed to the dry sandflat facies include the majority of the range of sedimentary structures described above for the damp sandflats although wave and current ripples, together with their associated silty drapes, are absent or rare. Also, importantly, the proportion of pinstripe and wind rippled laminae is increased, while wavy and irregularly laminated sandstones are less common. Dry sandflat intervals are recorded mainly within the cores from offshore East Irish Sea Basin wells and comprise only a minor percentage of the total sandflat intervals although it should be stressed that the

distinction between these intervals and both damp sandflat and aeolian sandsheet facies is necessarily somewhat arbitrary.

Dry sandflats typically comprise well to bimodally sorted fine and medium sandstones that are dominated by a regular flat lamination that includes very finely developed pinstripe lamination. Within the flat laminated intervals there are commonly very thin, sometimes only one grain thick, laminae comprising well rounded coarse sand grains (e.g. well 110/2-6, log depths 1088.95-1092.50m). In a number of instances the sandstones are strongly bimodally sorted with clear upward coarsening within individual laminae and isolated disruptions to the lamination in the form of small indentations in laminae surfaces (e.g. well 110/2-6, log depth 1106.15-1107.30m). Wavy and irregular lamination are present but tend to lack the thin silty partings and drapes that form an essential component of the damp sandflat facies and bioturbation is also rare.

The concordance of sedimentary structures between dry and damp sandflat facies, with the changes in proportions mentioned, implies a similar depositional environment, but one in which the relationship between the palaeo-water table and the sediment surface is allowing the wind reworking of that surface for a greater percentage of depositional time. Despite this, the dominance of wind rippling without any indication that larger aeolian bedforms were developed, suggest that the water table was never far below the sediment surface and, as discussed in connection with Stokes surfaces by Fryberger *et al.* (1988), was effectively controlling the sediment supply available for aeolian reworking. It is likely within this environment in which aeolian processes have become somewhat more important, that the thin coarse sand laminae represent minor deflation surfaces, while the small scale disruption of wind rippled laminae may represent either minor water escape structures at times of rising water table or, alternatively, the effect of rain prints on a wind rippled surface.

3.3.4 Aeolian sandsheet sandstones

Aeolian sandsheet sandstones occur in all logged sandflat sequences and, as with damp sandflats, comprise a major component of the non-channelised facies in the Sherwood Sandstone Group. They are recorded interbedded with damp and wet sandflat facies and with the aeolian dune sandstones described below from both wells in the offshore East

Irish Sea Basin and from outcrops at all stratigraphic levels where sandflats are preserved within the Cheshire Basin.

The sandstones range from fine to coarse grained and from very well to bimodally sorted within individual beds or laminae. Although not necessarily indicative of aeolian bedforms, there is a noticeable increase in the abundance of well rounded grains, especially in the larger grain size fraction, within these sequences suggesting at least that the grains have undergone aeolian transportation. The dominant sedimentary structure is a finely developed pinstripe lamination that can form sequences more than a metre in preserved thickness (Figure 3.24). The parallel laminated sandstones commonly exhibit an upward coarsening within laminae indicative of wind rippling (Fryberger and Schenk 1988). In favourable outcrops, especially those with considerable lateral extent, exposing aeolian sandsheet sequences it is noticeable that packages of wind rippled strata are bounded by very low angle discordant surfaces. In some instances the wind rippled laminae terminate against these surfaces, indicating that they can be erosional, and therefore form very low angle cross strata while in other cases the laminae are concordant to the upper bounding surface.

Minor soft sediment deformation is recorded in the form of water modification essentially the same as that described for the wind rippled laminae within dry sandflats above and also as sparse bioturbation. This latter includes c0.5cm diameter subvertical sand-filled burrows (e.g. Thurstaston Road Cutting, log depth 15.10m and Figure 3.25), rare sub-horizontal sand-filled burrows similar to *Planolites* and, somewhat exceptionally, *Skolithos* burrows up to 10cm long and c1.0cm in diameter that are recorded only in the core from well 110/14-3 (e.g. log depths 1084.00m and 1085.90m). The *Skolithos* burrows are also recorded within aeolian dune intervals in the same well and the implications of their presence is discussed further in Section 9.3 below.

While both dry sandflats and aeolian sandsheets include wind rippled strata as their dominant sedimentary structure, the distinction between them is based upon the near exclusive presence of this bedform and near absence of wavy or irregular lamination in the sandsheets. The identification of wind ripples is based largely upon the characteristic pinstripe lamination or inverse grading that has been previously described from both

Figure 3.24 Finely pinstripe laminated sandstones in the lower part of the outcrop representing wind rippled aeolian sandsheet overlain by the preserved remnants of a small aeolain dune and further aeolain sandsheet sandstones in a small road-side outcrop at Preston Brockhurst, south Cheshire Basin.

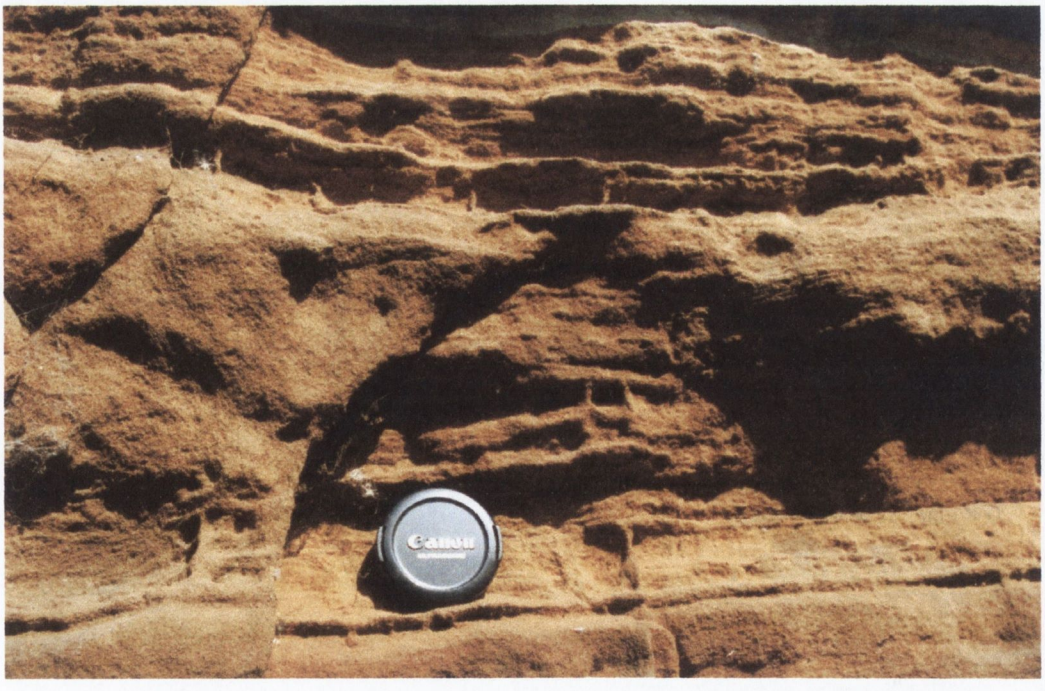


Figure 3.25 Flat laminated aeolian sandsheet sandstones at Thurstaston Road Cutting disrupted by preferentially cemented sub-vertical burrows.

modern and ancient aeolian environments (e.g. Hunter 1977; Clemmensen and Abrahamsen 1983; Fryberger and Schenk 1988). As described by these authors, pinstripe lamination represents incomplete preservation of wind rippled laminae within which the typical inverse grading is generated in response to sorting from the finest grains in the wind protected ripple trough to the most coarse grains available that collect by saltation at the ripple crest.

Aeolian sandsheets therefore represent a further stage in the continuum of sandflat environments. However, unlike the previously described wet, damp and dry sandflat facies, aeolian sandsheets also preserve larger scale aeolian bedforms as indicated by the low angle discordances that bound packages of wind rippled strata. These bedforms cannot be defined as aeolian dunes as they do not possess an active slipface but they do conform to the characteristic low relief rolling topography of modern aeolian sandsheets as described from the Great Sand Dunes National Monument in Colorado by Fryberger *et al.* (1979) and from Algodones in California and Padre Island in Texas by Kocurek and Nielson (1986). As with these examples, aeolian sandsheets in the Sherwood Sandstone Group are likely to have been controlled by a relatively high water table, although not so high relative to the sediment surface as those pertaining during the deposition of wet to dry sandflats, that effectively limited the sand supply available for building aeolian bedforms.

3.3.5 Aeolian dune sandstones

Aeolian dune sandstones are recorded interbedded with a variety of sandflat facies within the majority of well cores and Sherwood Sandstone outcrops where non-fluvial facies are preserved. It is, however, noticeable that preserved dunes tend to be larger and more abundant in wells and outcrops that are closer to presumed Early Triassic basin margins. For example, aeolian sequences in general and dunes in particular comprise a major component of the cored interval in well 110/14-3, less so in well 110/13-5 and are relatively rare in well 110/2-6 which lies some 25kms basinwards of these wells. Similarly, outcrops in the extreme south of the Cheshire Basin (e.g. The Cliffe and Nesscliffe) and those close to the Llyn-Rossendale Ridge which separates the present day Cheshire and East Irish Sea Basins (and is inferred to have been a positive feature during Sherwood Sandstone depositional time) and are in a favourable stratigraphic position (e.g.

Frodsham Village and Thurstaston Road Cutting) also preserve significant aeolian dune sequences.

Aeolian dune sandstones are moderate to well or locally bimodally sorted and range from fine to coarse sand grade with the coarser sand fraction commonly comprising well rounded sub-spherical to spherical grains suggesting aeolian transportation. In the majority of cases the dune bedforms comprise very fine parallel or pinstripe lamination identified as grainfall laminae (*sensu* Hunter 1977), while less common, slightly thicker (<1.0cm) and invariably coarser lamination can be ascribed to grainflow laminae (*sensu* Hunter 1977). In the larger dunes sedimentary structures are dominated by metre scale tabular cross stratified sets that, in logged sections, range up to a maximum of 2.70m (well 110/13-5, log depths 875.70-878.40) although dune sets with a preserved thickness in excess of this can be observed at Frodsham (Figure 3.26, dune thickness estimated as c.10.00m) and at Nesscliffe (est. >4.00m). Additionally, a dune set thickness that is variably c2.00->4.00m is logged at Thurstaston Road Cutting in a highly deformed aeolian dune sequence (log depth, 1.40-5.80m). Many of the aeolian dunes recorded in both cores and

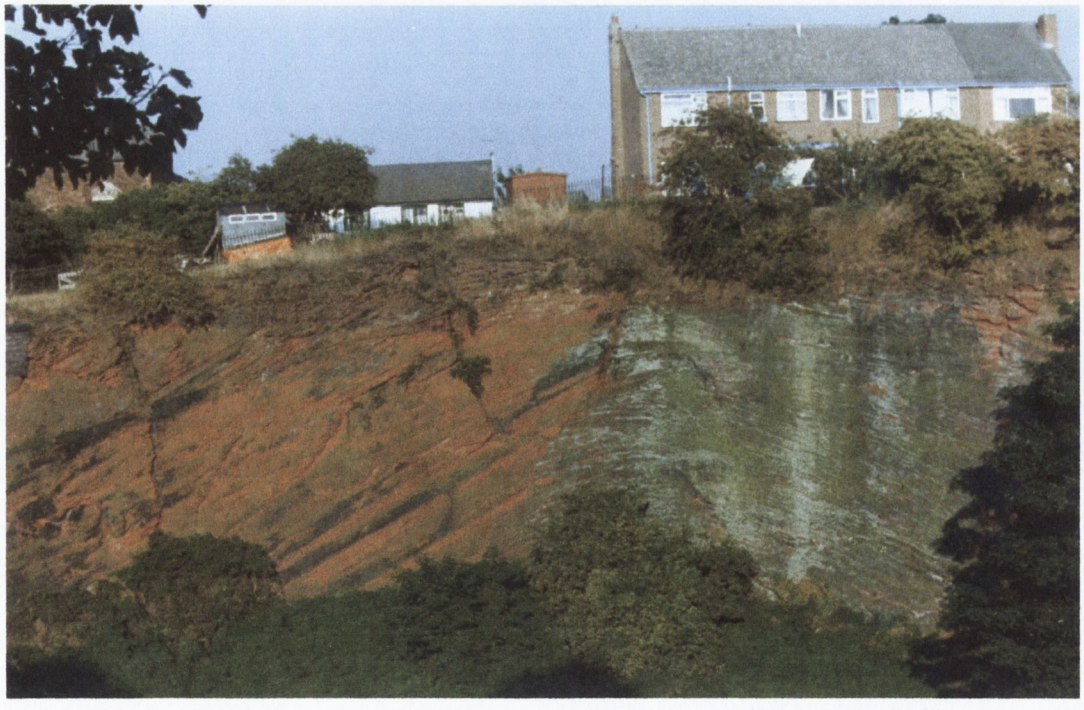


Figure 3.26 Large scale aeolian dune cross stratified sandstones exposed in the wall of a railway cutting at Frodsham. Foresets dip towards the viewer and can be traced along adjacent sides of a quarry in the side of the cutting where the quarry walls are at approximately 120°

outcrops are, however, less than one metre in preserved thickness and, in these smaller dune sets, asymptotic bases and trough cross stratification together with wind rippled toesets are abundant. Reactivation surfaces are also more common in these smaller dunes with individual dunes exhibiting rapid lateral variations in character from tabular cross stratification to long swept out foresets with wind ripples. At Thurstaston Road Cutting there are several examples of aeolian dunes that are approximately one metre at their maximum preserved thickness but can be seen to pass laterally into wind rippled aeolian sandsheets (Figure 3.27). Taken together, these aspects suggest that the majority of the smaller preserved dune sets represent depositionally small dunes rather than the preserved toesets of much larger bedforms.

The interpretation of these sandstones as the preserved remnants of aeolian dune bedforms is dependent, especially in cored intervals, on the character of the lamination which is considered to be typical and indicative of aeolian processes. This includes both wind ripple lamination as described above for aeolian sandsheets and the combination of grainfall and grainflow lamination indicative of deposition on, and migration of, aeolian dune slipfaces as described by Hunter (1977). Grainfall laminae are generated due to the fall out of grains that have been carried by the wind across the crest of an advancing dune and are then deposited on the slipface in response to flow separation and wind deceleration in the lee of the dune. By comparison, the generally slightly coarser grainflow laminae represent the accumulation near the dune crest of saltated grains that are transported up the stoss slope and then intermittently avalanche down the dune slipface.

The scale, geographical extent and stratigraphical distribution of preserved dune bedforms would appear to discount the presence of major aeolian dune fields during Sherwood Sandstone depositional time, with the possible exception of certain areas in the extreme south of the Cheshire Basin. Even where best developed and preserved, aeolian dunes in the Sherwood Sandstone Group are interbedded with other facies and rarely exhibit the complex and compound bedform associations of draas (*sensu* Wilson 1972) or compound, star or linear dunes as described by Lancaster (1988a). The larger dune bedforms, such as those at Nesscliffe, The Cliffe and logged in wells 110/14-3 and 110/13-5, probably represent either large isolated barchan dunes or parts of barchanoid ridges, while the smaller dunes are most likely to represent isolated parabolic or small barchan dunes.

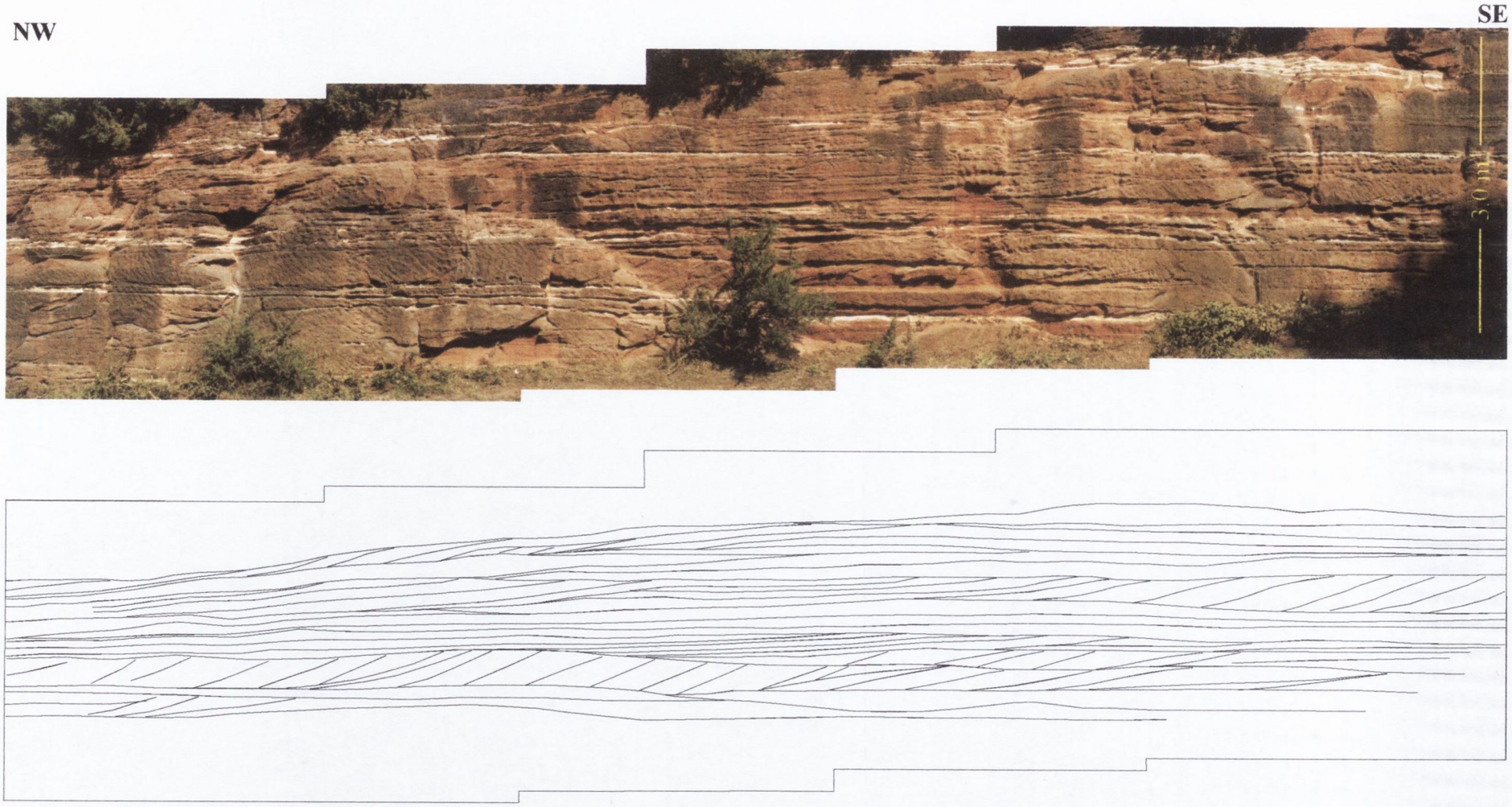


Figure 3.27 Aeolian sandsheet and aeolian dune remnants at Thurstaston Road Cutting, Wirral. Very low discordant surfaces within the sandsheets suggest an undulating palaeo-topography, while dune bedforms show lateral changes in thickness and character of cross stratification. Dominant aeolian transport directions are towards the NW, near parallel to the orientation of the cutting.

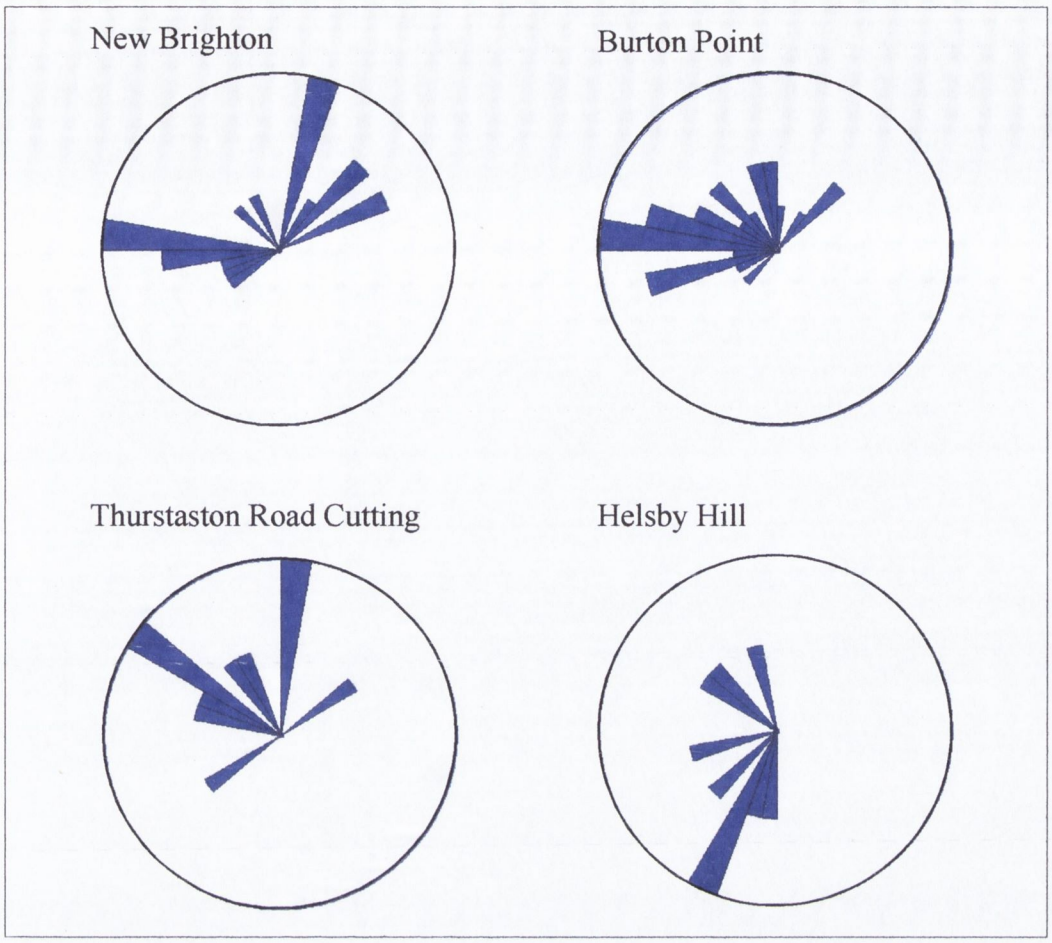


Figure 3.28 Rose diagrams for apparent palaeo-wind directions based on aeolian cross stratification from outcrops in the Cheshire Basin and the Wirral

Figure 3.29 Small parabolic dunes migrating across an undulating wind rippled aeolian sandsheet in Algeria. This represents a potentially viable modern analogue for the interbedded dune and sandsheet facies in the Sherwood Sandstone typified by the outcrops at Thurstaston Road Cutting, Figure 2.27.

Recorded palaeo-transport directions, based upon the azimuth of aeolian cross stratification reveal winds predominantly from the east and southeast (see particularly aeolian rose diagrams on logs for New Brighton, Burton Point, Thurstaston Road Cutting and Helsby Hill). When grouped for each locality (Figure 3.28) the rose diagrams reveal a marked bi-polarity consistent with the sinuosity of barchanoid ridges and/or the curvature of the horns of barchan to parabolic dunes (Figure 3.29). The inferred overall wind direction accords with previously published data (e.g. Thompson 1969; Mountney and Thompson 2002), an aspect discussed further in Section 3.6. Given that dune size is considered to be a function of both wind regime and sand supply (e.g.Lancaster 1988b), the suggested dune scale and morphology accords with discussions above regarding the presence of a relatively high water table throughout much of Sherwood Sandstone depositional time. Despite the obvious abundance of sand grade sediment in the Early Triassic basins of N.W. England, a consistently high if fluctuating water table would have effectively limited the availability of sand and placed constraints on the size of aeolian bedforms that could be generated.

3.3.6 Clastic sabkha sandstones and anhydrites

Sequences that can be described as 'sabkha' are positively recorded only within the cored interval from well 110/8a-5 although a small outcrop adjacent to the logged intervals at New Brighton (Figure 3.30) exhibits sedimentary characteristics that are somewhat similar but more finely laminated although evidence of evaporite cements could not be found in the outcrop. Within well 110/8a-5 the clastic sabkha intervals occur only within the uppermost c30m of the core and, due to the position of the recovered core high in the Ormskirk Sandstone Formation, the uppermost formation in the Sherwood Sandstone Group, these intervals are located directly beneath the Sherwood Sandstone Group to Mercia Mudstone Group contact in this well.

Within this upper interval in the cores from well 110/8a-5 there are several discrete sequences, generally decreasing downwards in both preserved thickness and intensity, within which evaporites, mainly anhydrite with subordinate dolomite, are abundant. The early evaporite cements, as described by Thompson and Meadows (1997), are generally sediment supported and form conspicuous millimetre to centimetre scale laminae, discrete nodules up to 1cm diameter and dispersed fine partings. These evaporites occur within sandstone dominated intervals exhibiting a irregular flat lamination not unlike that

Figure 3.30 Very finely and irregularly laminated fine silty sandstones at New Brighton, Wirral. The laminated facies can be traced for over 100 m laterally and is interbedded with damp sandflat and aeolain sandsheet sandstones. The light grey partings and blebs are interpreted as remnant evaporite cements, possibly anhydrite, now dissolved and replaced by clay.

described for parts of the damp sandflat facies above but generally developed on a finer scale. In places, the nodules are reworked into the bases of cross stratified sets associated with either sheetfloods or isolated fluvial channel fills that are otherwise devoid of early evaporite cements. Soft sediment deformation is ubiquitous in the evaporite-rich intervals and occurs as relatively gentle contortions or doming to intense deformation characterized by partially homogenized fabrics (Figure 3.31).

Petrographical analysis of the anhydrites within evaporite-rich laminae has shown that they exhibit a felted texture with sub-parallel arrangements of laths that is typical of an early evaporitic origin (Thompson and Meadows 1997 and Figure 4.15). Similarly, the closely associated dolomites display a sucrose texture that is distinct from later burial-related cements. Geochemical work on these evaporite-rich sequences, on anhydrite cements in the upper Ormskirk Sandstone Formation and in the overlying Mercia Mudstone Group (Greenwood and Habesch 1997) has shown from isotopic analysis that there is a remarkable consistency in $\delta^{34}S$ values and that these conform to published data for Early Triassic seawater (Claypool *et al.* 1980; Veizer *et al.* 1980). This latter data has been used

and supported by Naylor *et al.* (1989) in examination of evaporites within the Mercia Mudstone Group where a similarly marine influence is suggested.

It is has been suggested, based on the foregoing analyses and descriptions, that the early evaporitic cements within the uppermost parts of the Ormskirk Sandstone Formation in this well have a marine source and a model of evaporite precipitation within a clastic sabkha environment has been proposed for these sequences by Thompson and Meadows (1997). These authors used the presence of the clastic sabkhas as support for a model of diachroneity at the contact between the Sherwood Sandstone and Mercia Mudstone Groups with the envisaged depositional environment near the top of the Ormskirk Sandstone Formation being similar to the present-day situation on the western coast of the Arabian Gulf around Dhahran as described by Fryberger *et al.* (1983). In this area prevailing offshore winds supply abundant sand to the coastal area leading to a fine interdigitation of wind-blown sand and water table derived, potentially marine influenced, evaporites. This situation is analogous to that in the Ormskirk Sandstone Formation where published data on the Early Triassic prevailing wind regime (e.g. Thompson 1969), supported by data in this study suggest a mainly easterly component leading to sand inundation around the eastern margins of the eastwards and southwards transgressing marine incursion (see

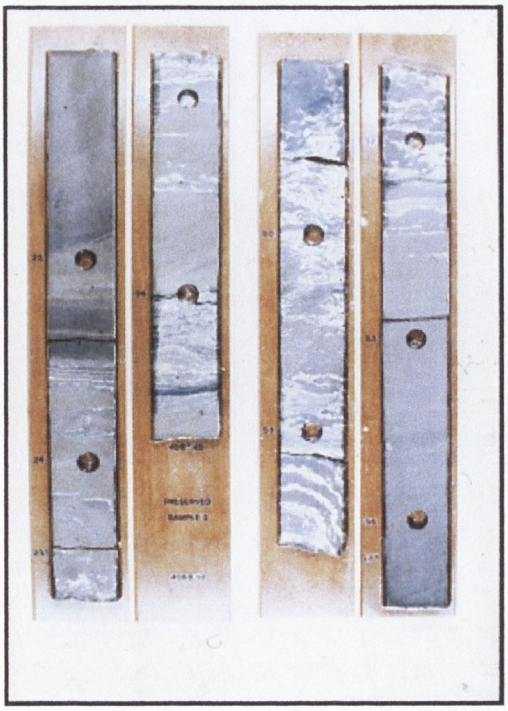


Figure 3.31
Well 110/8a-5, core depths 1244.60-1248.50 m. Clastic sabkha facies comprising anhydrite cemented fine sandstones with disrupted laminae and nodules of primary anhydrite interbedded with sheetflood and fluvial channel sandstones.

discussions below in Sections 3.6 and 9.7).

3.4 FLOODPLAINS

3.4.1 Playa lake siltstones and claystones

Fine grained sequences that can be related to deposition within standing bodies of water form a minor but significant proportion of the Sherwood Sandstone Group succession. These sequences are recorded mainly in cores recovered from the offshore East Irish Sea Basin wells where they occur within the Ormskirk Sandstone Formation and also from outcrops exposing the basal succession of the Sherwood Sandstone Group at Saltom Bay in west Cumbria (see below). A sparse number of outcrops in the Cheshire Basin do include fine grained intervals but these are predominantly interpreted as fluvial abandonment deposits and are described above in Sections 3.2.5 and 3.2.6. Only at Raw Head are laterally extensive, in so far as outcrop allows, claystones and siltstones exposed that may well represent the preservation of playa lake fines although these are in part pedogenically modified (Figure 3.32 and log depth 10.90-11.25m, Appendix II).

Siltstones and claystones with interbedded very fine or fine sandstones occur at several horizons in the cores recovered from the Ormskirk Sandstone Formation in offshore wells but the most extensive is that referred to colloquially by operators in the East Irish Sea Basin as the 'Century Playa.' The informal name derives from the fact that this playa sequence is recorded approximately 100ft below the base Mercia Mudstone Group to top Sherwood Sandstone Group contact across the majority of the Morecambe Field. The 'Century Playa' can, however, be traced and correlated across much of the basin into wells as far north as 113/26-1 and south to 110/20-1. In well 110/2-6 it exhibits a typical facies association of finely laminated to blocky claystones and argillaceous siltstones locally disrupted by load structures and sand-filled desiccation cracks (log depth 961.40-963.35m and Figure 3.33). The interbedded very fine, fine and locally medium sandstones are also generally flat laminated but can be current or wave rippled and quite commonly have rip-up clasts of claystone and siltstone, similar to those interbedded with the sandstones, incorporated in the base of beds. Although not present in this particular interval, playa lake deposits elsewhere are commonly also disrupted by bioturbation including mainly 0.2-0.5cm diameter either sub-vertical or sub-horizontal sand-filled burrows that, in the latter instance, have some similarity to the shallow marine *Planolites* ichnogenera.

Figure 3.32 Finely laminated and blocky red claystones and siltstones interpreted as playa lake fines with pedogenic modification exposed beneath fluvial channel sandstones at Raw Head, Cheshire.

The claystones and siltstones that form a significant component of the playa lake facies clearly indicate deposition by suspension settling of fines within standing water bodies. The presence of sandstones with evidence of traction carpet sedimentation and of desiccation cracks, however, suggests that the lakes were never more than a few metres deep at most. The presence of wave ripples also suggests extremely shallow water depths, while the blocky nature of some intervals within the claystones may also indicate incipient pedogenesis, potentially representing the formation of peds in a near surface position during dry episodes (sensu Marriott and Wright 1993), and would further support suggestions regarding the ephemerality of the playa lake environment. The playa lake sequences logged for this study show no evidence of being evaporitic although sparse halite psuedomorphs have been recorded previously (Meadows and Beach 1993). Despite their shallowness and ephemerality some of the playa lakes, especially the 'Century Playa,' are correlatable between wells (see Sections 3.6 and 6.2) and, hence, must have been of considerable lateral extent. As with the evidence cited above concerning sandflat environments generally in the Cheshire and East Irish Sea Basins, it seems likely that during times when playas were at their maximum development there was little topographic relief across substantial areas of these basins.

Figure 3.33
Section of core from well 110/2-6 at core depth 961.40 m. Sand filled desiccation cracks cut through playa lake claystones.

The inferred playa lake sequences at the basal contact of the Sherwood Sandstone Group with the underlying Barrowmouth Mudstone Formation of the presumed Permian Cumbrian Coast Group are, however, potentially even more extensive and significantly thicker. They are exposed in a series of small outcrops in west Cumbria (including Saltom Bay, log depth 23.70-26.20m) where, despite some slight stratigraphic uncertainty, they reach a preserved thickness of approximately 60m overlying dolomites and anhydrites of the St Bees Evaporites Formation. This succession, as logged, comprises laminated and blocky siltstones with interbedded laterally extensive fine sandstones (Figure 3.34) exhibiting current ripples, wave ripples and desiccation cracks that pass upwards into lacustrine fluvio-deltaic sandstones (section 3.4.3). Offshore the Barrowmouth Mudstone Formation reaches a maximum of 185m in well 113/26-1 and can be correlated across a major area of the northern and central East Irish Sea Basin (see Section 8.3). If all or any significant part of this succession can be inferred to represent playa lake environments then there was clearly a much more substantial development at this time than at any during the deposition of the Sherwood Sandstone Group. An equivalent succession, the Manchester Marl Formation, is present in the Cheshire Basin but outcrops are few and very poorly exposed such that there is little sedimentological data on which to base any interpretation. As discussed above, however, the presence of blocky claystones suggests the possibility of incipient pedogenesis and again provides an indication of the ephemerality of the playa lake within this claystone dominated succession.

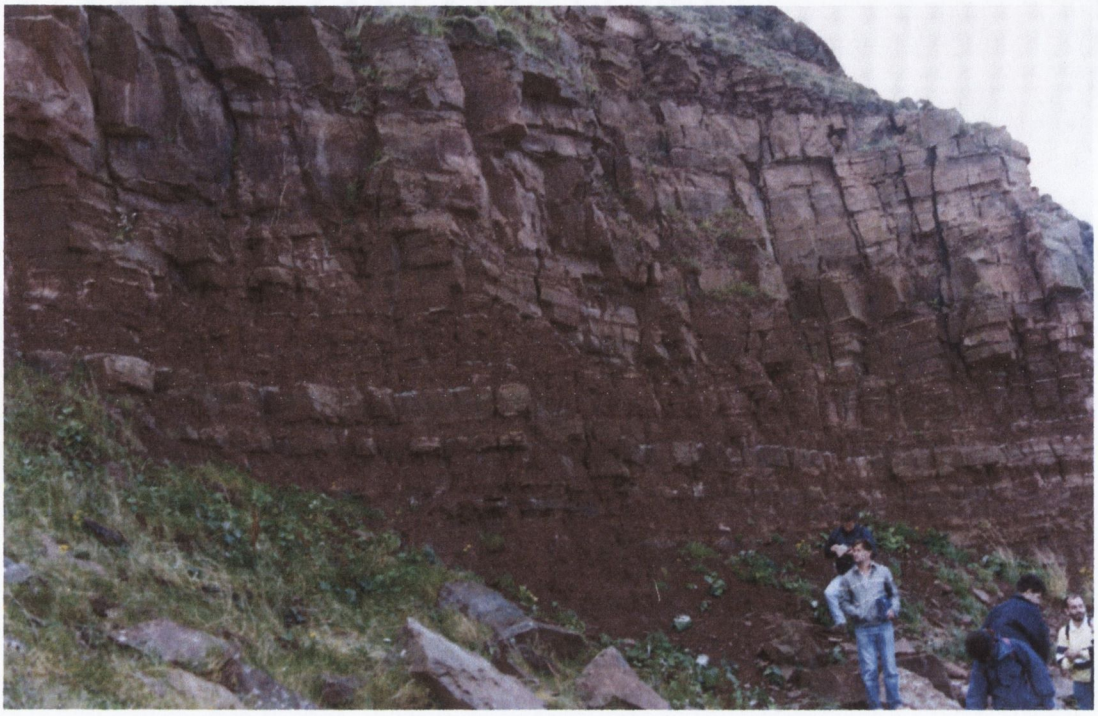


Figure 3.34 Red blocky claystones and siltstones of the Barrowmouth Mudstone Formation exposed at Saltom Bay, west Cumbria. Interbedded thin laterally extensive fine sandstone beds represent lacustrine pro-delta, while the overlying sandstones represent lacustrine delta progradation.

3.4.2 Playa margin sandstones, siltstones and claystones

Playa margin deposits are identified principally from their close association with the playa lake sequences described above and, as such, are also recorded mainly in the wells of the East Irish Sea Basin and within the Ormskirk Sandstone Formation.

These sequences comprise laminated fine and very fine sandstones exhibiting current and wave ripples interbedded with thin finely laminated siltstones, all of which are commonly bioturbated with a range of burrow forms including sub-vertical and sub-horizontal sand-filled types generally in the range 0.2-0.5cm diameter. Soft sediment deformation is also common with loaded bases to sandstone beds and sand-filled desiccation cracks within the siltstones.

Sequences interpreted as representing a playa margin environment are seen as being essentially transitional between the deposits of playa lakes and wet to damp sandflats. They exhibit many of the sedimentary characteristics of both facies but tend to be somewhat more sandstone dominated than playa lake deposits *sensu stricto* and exhibit

greater evidence of standing water, in the form of wave ripples and siltstone laminae than those designated wet sandflat facies. It is possible that they simply represent significant inputs of sand grade material into a playa lake although the compelling evidence for ephemerality in the playa lakes implies episodic expansion and contraction of the lakes, thereby exposing the margins to sandflat processes equivalent to those discussed above in Sections 3.3.1 and 3.3.2.

3.4.3 Lacustrine delta sandstones

Sandstones interpreted as resulting from fluvial incursions into standing water bodies of significant extent are recorded only in the logged interval from outcrops at Saltom Bay in west Cumbria. This succession represents the basal sequences of the Sherwood Sandstone Group in this area where they supposedly overlie the St Bees Evaporites of presumed Late Permian age (see Figure 1.2). Equivalent sequences are presumed to have been penetrated in offshore wells that were drilled to these stratigraphic horizons but this cannot be confirmed due to the absence of any core recovery (but see discussion below in Section 8.3).

Sandstones ascribed to a lacustrine delta setting are generally fine grained with sedimentary structures dominated by flat lamination or very low angle cross stratification within beds that rarely exceed a few 10s centimetres in preserved thickness. The tops of beds are locally current rippled, while bases tend to be non-erosive to underlying siltstones. In general, the sandstone beds can be traced for the full extent of the available outcrop but this is less than 20m at these localities and the full lateral extent of the beds is therefore unknown. Where compound sequences are preserved (e.g. Saltom Bay, log depths 6.05-6.40m and 11.10-11.60m) they can be seen to form an overall upward coarsening profile that passes conformably upwards into laterally discontinuous fluvial channel sandstones (Figure 3.34). Higher up the exposed succession at Saltom Bay the sandstone beds can be seen to exhibit sharply defined tops overlain by claystones and siltstones suggested to represent flooding and re-establishment of the lacustrine environment (Figure 3.35).

The lacustrine delta interpretation placed upon the sandstones described here is based largely on their association with overlying fluvial channel sandstones and underlying lacustrine fines as previously described. The sedimentological character and lateral extent

Figure 3.35 Interbedded lacustrine fluvio-deltaic sandstones and playa lake fines representing alternating lacustrine lowstand and highstand sequences at Saltom Bay, west Cumbria.

of the lower sandstones within the delta complexes appears to preclude their deposition within channels or, at least within channels of the dimensions typical of the overlying sandstones with which they are closely associated. They are, however, clearly genetically related to the fluvial channel sandstones in that their observed mineralogy and grain shape clearly derive from the same source, the lacustrine delta sandstones merely representing a finer grain size fraction of the same bulk composition. Additionally, their non-erosive association with the underlying lacustrine fines suggests deposition in the same environment as an integral part of the prograding fluvial system represented by the channel sandstones.

3.4.4 Sheetflood sandstones

Sediments ascribed to deposition by unconfined fluvial processes form a minor component of the Sherwood Sandstone Group successions and are most commonly recorded interbedded with aeolian, sandflat and playa lake sequences.

Sheetflood deposits vary from flood reworked aeolian sandstones to finely laminated silty and argillaceous distal lacustrine sandstones. Primary depositional structures include plane

bed lamination, low angle cross stratification, current ripples and, sparsely, wave ripples, the latter commonly with form concordant siltstone drapes. In the majority of cases there is little or no evidence to suggest erosion at the base of the sandstone and, where exposed in favourable outcrops, these beds can be seen to be laterally extensive with only minor thinning over tens of metres (e.g. Saltom Bay and New Brighton, see logs in Appendix II). The range of structures suggests deposition from recurrent, rapid bedload sedimentation events either across a sandflat surface or into a shallow standing water body. In the latter instance the subsequent cessation of flow and fall-out of suspension fines would account for the wave rippled tops to these sandstones and their siltstone drapes.

While a crevasse origin related to the flooding and overbanking of active channels may account for a proportion of the sheetflood sandstones (notably that at New Brighton which can be directly related to a adjacent channel, Figure 3.36), it is equally likely that contemporaneous flooding of the sandflats in response to rainfall may have generated localised flows, especially wherever some topographic relief was maintained. In the case of the sheetflood sandstones associated with the larger playa lake succession at the base of the Sherwood Sandstone Group and potentially in the Barrowmouth Mudstone Formation, it appears most likely that these were sourced from the front of the prograding fluvio-lacustrine delta. In this sense, these particular sandstones may be better regarded as lacustrine pro-delta rather than sheetflood but their similarity of sedimentary structures to sheetflood sandstones *sensu stricto* would render separate description repetitive.

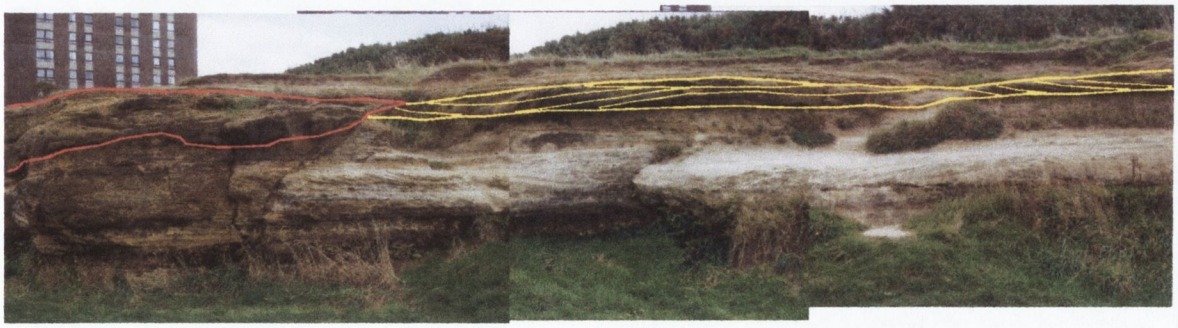


Figure 3.36 Stacked thin sheetflood sandstones (outlined in yellow) interbedded with aeolian sandsheet and damp sandflat sandstones and lying adjacent to an isolated fluvial channel fill (outlined in red). The close proximity and similar grain population suggest derivation of the sheetfloods by overbanking of the channel. New Brighton

3.4.5 Vegetated floodplain sandstones, siltstones and claystones

Sequences with evidence for plant colonization are extremely rare in the Sherwood Sandstone Group in either the East Irish Sea or Cheshire Basins. Elsewhere, in sequences of equivalent age, palaeosol development is significantly more abundant as, for example, in the Sherwood Sandstone Group of the Wessex Basin, southern England, where calcrete formation is a common occurrence both at outcrop (Edmonds *et al.* 1975) and in the sub-surface (Bowman *et al.* 1993).

Within the present study, intervals with any evidence of palaeosol development are recorded only in the cored interval from well 110/2-6 and at Raw Head in the central Cheshire Basin and at Hawkstone Park in the south. The palaeosols in well 110/2-6 comprise highly disrupted silty and argillaceous very fine sandstones and admixed siltstones with scattered fine sand grains that are recorded at log depths 1001.35-1002.40m and 1082.40-1084.10m in well 110/2-6. In both of these intervals intense rootlet disruption has resulted in the complete obliteration of any primary sedimentological structures such that only a churned fabric remains with traces of sub-vertical branching rootlet impressions. In the lower cored interval there are reduction spots associated with the rootlets and also some limonite nodules. At Raw Head potentially calcrete related concretions are preserved mainly within poorly sorted fine sandstones ascribed to a damp sandflat environment directly overlying sheetflood sandstones and playa lake siltstones (Figure 3.37). The presence of calcretised sandstones is recorded in the south of the Cheshire Basin (Meadows and Maguire 1997) in the grounds of Hawkstone Park where they form well developed rhizocretions (Figure 3.38).

The presence of rootlet disrupted intervals and sparse calcretes provides evidence that some plant colonization did occur within the Sherwood Sandstone Group although the sparse occurrence of such sequences suggests that this was extremely rare. Where they do occur they appear to represent rather different palaeosol types with those in the Cheshire Basin, typified by caliche development, conforming to aridisols as defined by Retallack (1997; 2001), while those in well 110/2-6 are closer to the characteristics of mollisols or vertisols. This difference may simply reflect differences in elevation relative to the prevailing water table or to the time available for soil development. However, considering the high water table conditions that are considered to be a prerequisite for the development

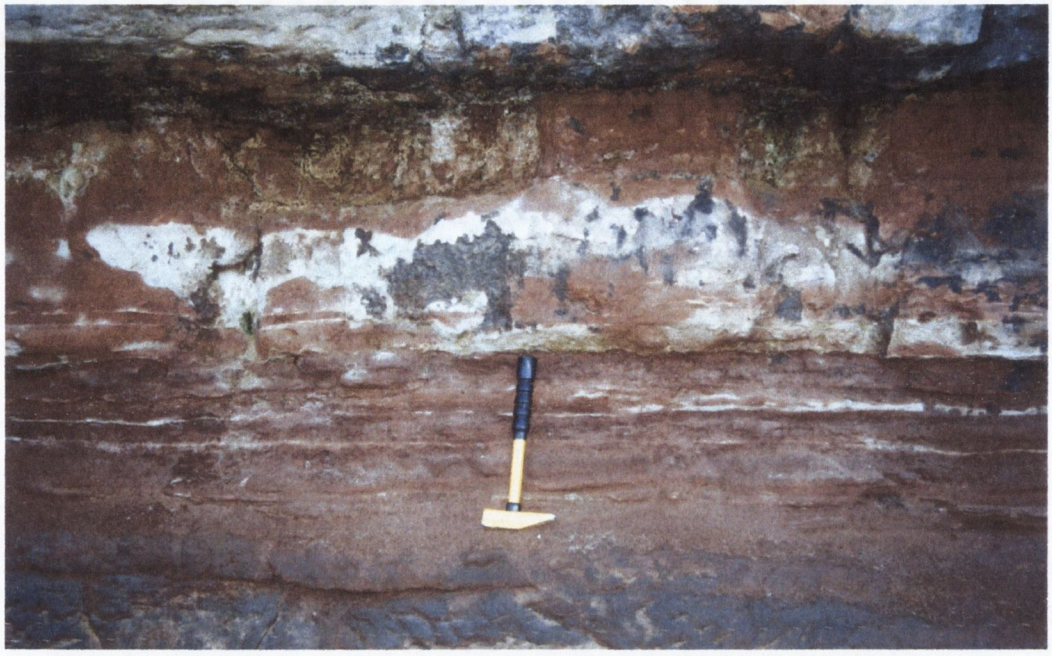


Figure 3.37 Diffuse calcrete nodules and laminae within damp sandflat siltstones and sandstones at Raw Head, Cheshire. It is likely that the palaeo-surface to which the pedogenesis related has been eroded prior to the deposition of the fluvial channel sandstones directly above.

Figure 3.38 Calcrete nodules and downward branching rhizocretions within fluvial channel sandstones at Hawkstone Park, Cheshire. The calcretised root systems project downwards from the prominent erosion surface that is overlain by aeolian dune sandstones

of sandflats it seems strange that such sequences are not more common, particularly in view of the abundant bioturbation that accompanies and disrupts playa lake, wet to dry sandflat and even aeolian successions. It is feasible that saline porewaters prevailed through much of Sherwood Sandstone depositional time, thus precluding significant plant colonization but, if so, then the evaporites have left little evidence of their presence in the sedimentary record.

3.5 ALLUVIAL FANS

3.5.1 Alluvial fan conglomerates and sandstones

A series of small outcrops around the village of Alberbury in the extreme south of the Cheshire Basin expose interbedded sandstones and conglomerates that have previously been referred to the Alberbury Breccia (Pocock *et al.* 1938). This has been included in subsequent BGS publications up to and including Plant *et al.* (1999) where it is shown on the accompanying map but is not referred to by Warrington *et al.* (1999) in the same publication.

The accessible outcrops reveal approximately 3m vertically of very poorly sorted conglomerate with rather angular clasts ranging from granule up to small cobble grade, locally clast supported but mainly matrix supported within a tightly calcite cemented moderate to coarse sandstone (Figure 3.39). The identifiable clasts include quartz, especially vein quartz, chert, possible limestone and metamorphic rock fragments, the latter dominated by quartz and mica with a schistose fabric. Conglomeratic beds appear, on the scale of the limited outcrop, to be laterally continuous with little thickening or thinning.

Figure 3.39
Alluvial fan conglomerates comprising locally derived quartz, limestoneand schist clasts in a sandstone matrix. There is no regional dip as far as can be determined from available outcrop and the dip of bedding is presumed to be depositional, Alberbury, southern Cheshire Basin.

The conglomerates are interbedded with fine to medium sandstones forming decimetre scale generally flat laminated beds but with some sets exhibiting low angle cross stratification and other thinner beds showing pinstripe lamination.

The sandstones are comparable with facies described above as sheetflood and aeolian sandsheet sandstones respectively. The conglomerates do not bear comparison with any of the pebbly sandstones ascribed to deposition within fluvial channels as described above. It seems likely from the angularity of the clasts that they are locally derived and have not been transported any great distance before deposition. This together with their interbedding with sandstones that are clearly sandflat related would suggest an alluvial fan setting in which episodic flows across the fan surface, transporting sediment from near-by exposures around the basin margin of Carboniferous rocks and metamorphosed Lower Palaeozoics, interdigitated with sand reworking across a broad low relief sandflat occupying the southern extremity of the Cheshire Basin.

3.6 SEDIMENTOLOGICAL MODEL

The facies described from the Sherwood Sandstone Group succession can be divided into those related to the filling of fluvial channels and all non-channelised facies including sandflats, floodplains and alluvial fans (Figure 3.40). Although the sedimentological models for these two groups of facies are discussed here separately, it is recognised that they must have co-existed and that, as discussed below in Sections 6 to 9, an appreciation of the lateral and vertical relationship between fluvial channel facies and their non-channelised counterparts is essential to an understanding of Sherwood Sandstone stratigraphy and palaeogeography.

It has been recognised for some time that for much of Sherwood Sandstone Group depositional time a fluvial system operated through the Cheshire and East Irish Sea Basins flowing northwards from central and southern Britain and exiting northwards into the Solway Basin (e.g. Wills 1951 and 1970; Audley-Charles 1970), or possibly at times eastwards into the Peel Basin (see Section 6 below). The most likely entry point for the fluvial system into the Cheshire Basin is from the Stafford Basin across the Hodnet Horst in the area between Preston Brockhurst and Blakenhall (see Figures 1.4 and 1.5).

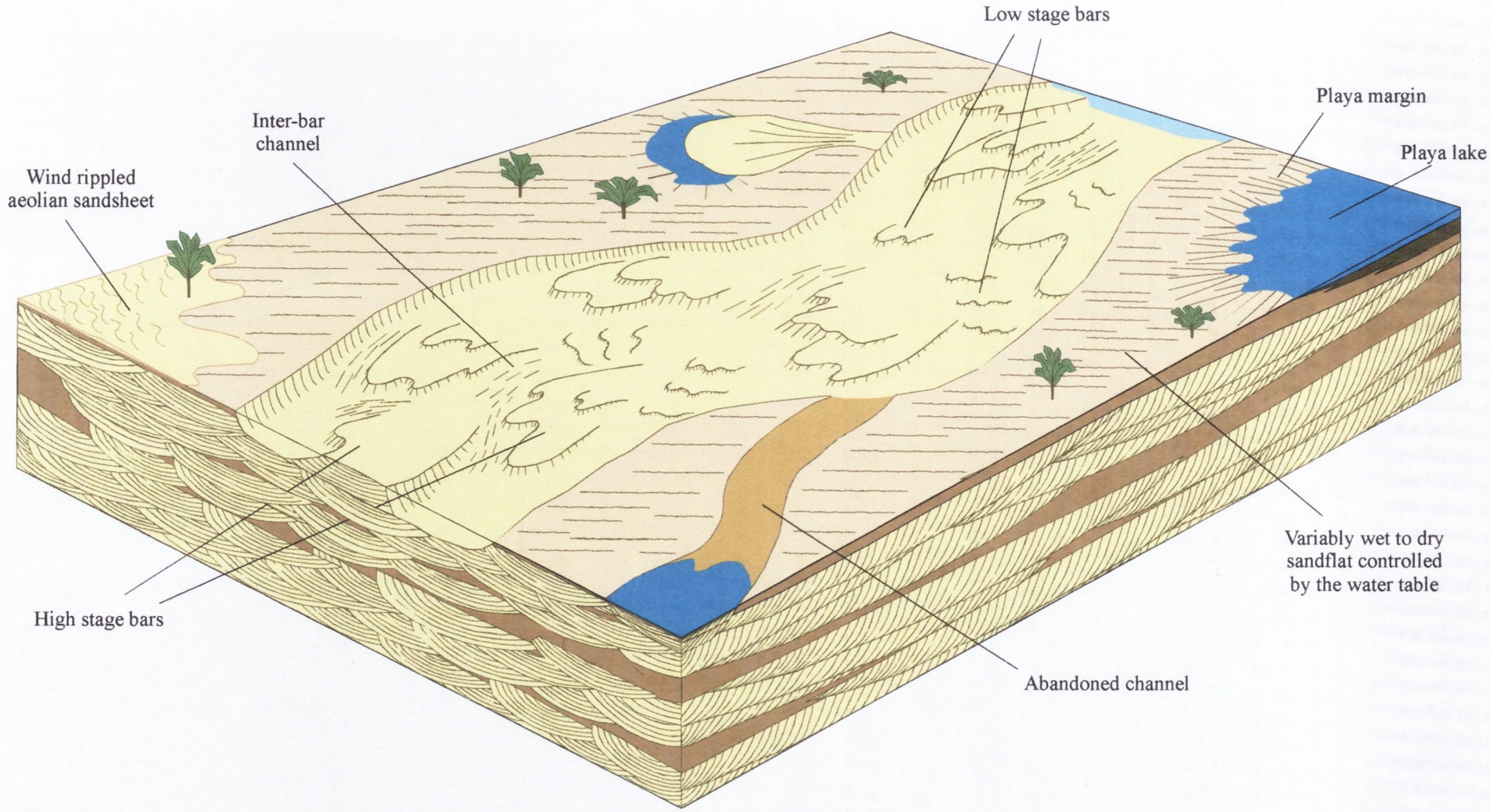


Figure 3.40 Schematic depositional environments for the Sherwood Sandstone Group in the East Irish Sea and Cheshire Basins

Presumed fluvial channel sandstones are recorded in the western parts of the Stafford Basin (Pocock *et al.* 1938 refers to Pebble Beds in this area), wireline log data suggests they are present in the Prees-1 well and a major fluvial channel is recorded with palaeocurrents to the NW at the Red Hills locality (Figure 3.41). All wells and larger outcrops north and west of this area include fluvial channel sandstones but, by comparison, there are no such sequences known south of the Prees-1 well in the Cheshire Basin.

It is likely that the fluvial system was of low to moderate sinuosity with an extremely sand-rich bedload comprising mainly fine to medium sand with a scattering of pebbles that become progressively more scarce northwards. The bedload formed a broad range of bars representing various stages of the flow regime within the channels and it is the variability of the bedforms that allows the differentiation of sub-environments within the channel system. These can be related to major high stage and compound bars formed during peak discharge and essentially bank-full conditions, minor or low stage bars and dunes representing intermediate water levels that would have formed within an anastomosing network of channel anabranches diverted around the major bedforms and plane-bed lamination or very low relief bedforms that formed at the lowest stages of maintained flow in response to acceleration between bars as the anabranches degenerated into a pool and

Figure 3.41
Fluvial channel with markedly erosive base incised into damp sandflat and aeolian sandstones at Red Hills. This locality lies near the crest of the Hodnet Horst and marks a potential entry site for the Sherwood Sandstone fluvial system from the Stafford Basin into the SE margin of the Cheshire Basin. Palaeocurrent data indicates flow directions to the west.

riffle system. At times some of the channel anabranches became abandoned, allowing ponding to occur with the consequent deposition of suspension fines although, from the abundance of reworked claystone and siltstone intraclasts incorporated within bar sandstones, it is clear that much of this fine grained material was eroded and reworked by subsequent flood events.

The depositional products of the changing flow regime can be recognised as components within channel filling sequences that, in favourable outcrops (e.g. Fleswick Bay and Bromborough Beach) display high levels of heterogeneity (see Figure 3.10). This evidence for significant variability in the flow regime suggests a fluvial system with a high discharge ratio, potentially responding to a seasonal climate in which wet season floods and bank-full conditions alternated with dry season droughts and severely reduced flow. Such a concept accords with published models of the Triassic climate that suggest a global monsoonal circulation pattern in response to the aggregation and distribution of the super-continent Pangea (Simms and Ruffell 1990; Dubiel *et al.* 1991; Parrish 1992). There is, however, compelling evidence in the form of the abundant low stage bedforms that the fluvial system was more likely to have been perennial rather than ephemeral. It appears that although displaying a high discharge ratio that may well have reduced channels to network of small streams wandering between the major bedforms during the dry season, the catchment area supplying the system was of sufficient extent to maintain some flow throughout the year.

This supposition accords with published accounts of the early Triassic palaeogeography (e.g. Audley-Charles 1970; Warrington and Ivimey-Cook 1992) and inferences regarding the potential source of sand grade material transported by the Sherwood Sandstone rivers (Fitch *et al.* 1966) that suggest potential hinterlands in southern Britain and northwest France. Warrington and Ivimey-Cook (1992) in particular, drawing on numerous previous authors, map the extent of this fluvial system and show sedimentary linkage of structurally discrete basins from the English Channel to the East Irish Sea. Published palaeocurrent data from the onshore areas (Wills 1951; Audley-Charles 1970; Warrington and Ivimey-Cook 1992) reveals a consistent northwards transport direction along the course of the suggested river. Conversely, Warrington and Ivimey-Cook (*op. cit.*) also indicate westwards and southwards transport directions for similar age fluvial systems in the

Solway Basin and on Aran to the north. On this basis these authors suggest that the marine transgression responsible for the onset of Mercia Mudstone Group sedimentation entered the East Irish Sea Basin from the SW via the Celtic Sea and Cardigan Bay Basins. This is counter to the findings of Musgrove *et al.* (1995) who map the position of the Variscan Front across the Celtic Sea, suggesting this to be the southern limit of significant Sherwood Sandstone deposition in this area, and show a northwards thickening Sherwood Sandstone Group supplied by fluvial systems originating in the Variscan Highlands to the south. The possibility arises that the palaeocurrent data from Solway and Aran reflects only local transport directions associated with potentially tributary systems and that the main Sherwood Sandstone Group fluvial system continued northwards and may be preserved in the deeper parts of the North Channel and Rathlin Basins as inferred by Maddox *et al.* (1997).

Sandflat, floodplain and playa lake facies can be seen as comprising a continuum of depositional environments operating beyond the immediate reach of the fluvial channel system. Across this range the relationship between the sediment surface and the palaeo-water table is of paramount importance in determining the conditions under which sediment was deposited and potentially preserved. At times, and in places, where the palaeo-water table was relatively high any aeolian processes would have been inhibited and deposition would have been controlled by either standing water bodies or by unconfined fluvial activity. The source of any sheetfloods is largely conjectural but could represent either overbanking of adjacent channels as shown at New Brighton (Figure 3.36) or the effects of hinterland flood events in response to flash floods. Such floods would have contributed to any playa lakes within sub-basinal lows although it is likely that such features would have been transient with minor changes in the water table resulting in significant expansion or contraction of these playas. Episodes during which the water table was relatively high probably also account for the few vegetated floodplain sequences recorded in well 110/2-6 as this would have reduced any salt concentrations, potentially allowing colonisation, while playa lake and playa margin sequences, with their high clay and silt contents, would have provided a suitable substrate.

As thus described, the majority of the sandflat successions within the Sherwood Sandstone Group appear to conform reasonably closely to the wet aeolian system of Kocurek and

Havholm (1993). The preservation, and dominance, of wet to dry sandflat facies (referred to interdune accumulations by these authors) over aeolian bedforms *sensu stricto* suggests a system typified by a high water table and relatively low angle of climb. It is clear, however, that significant intervals of the Sherwood Sandstone Group succession contain no aeolian bedforms whatever and these models may be only partially applicable.

Interbedding of Sherwood Sandstone Group fluvial and fluvio-lacustrine sandstones with the siltstones and claystones of the supposedly underlying Barrowmouth Mudstone Formation in the northern parts pf the East Irish Sea Basin (e.g. Saltom Bay sedimentological log) provide evidence for more substantial playa lake development than elsewhere in the succession. The mudstones, presumed to be lacustrine in the offshore wells although evidence is sparse, can be traced across the entire northern and central East Irish Sea Basin and, if the interpretation is correct, therefore represent a significant lake development prior to and partially coeval with the basal sequences of the Sherwood Sandstone Group (see discussion in Section 8.3 below).

With a fall in the palaeo-water table relative to the sediment surface, aeolian processes would have been initiated and then progressively become dominant, first with the adhesion of wind transported particles to a damp substrate giving rise to the characteristic irregular or wavy lamination of damp sandflats. Increased evaporation associated with such a change would also have increased the likelihood of evaporite cement precipitation in the near sub-surface potentially generating the irregular textures discussed by Herries and Cowan (1997). With further falls in the relative palaeo-water table the drying transition would have continued with the development of thin wind rippled laminae that represent the first stage of aeolian sandsheet formation. Low relief aeolian bedforms, dominated by wind ripple lamination, tend to form in areas of limited sand supply (Kocurek and Nielson 1986) and, in the Sherwood Sandstone Group, they are most commonly recorded as an intermediate facies between wet or damp sandflats and aeolian dune facies. The overall abundance of sand grade detritus in the Early Triassic basins implies a control other than gross sand supply in order to limit that available for building aeolian bedforms and, given the comments above regarding the relationship between the palaeo-water table and damp sandflat facies, it is reasonable to infer that the proximity to the palaeo-surface of the water table remained the principal control on the sand supply.

Ultimately, as the availability of sand increased, dune scale aeolian bedforms would have developed and migrated across the wind rippled sandflat surface. With the possible exceptions of certain areas in the extreme south of the Cheshire Basin and across parts of the Llyn-Rossendale Ridge (as discussed above in Section 3.3.5) it is unlikely that large aeolian dune fields were established during Sherwood Sandstone depositional time. The common occurrence of sub-metre scale aeolian dunes and their interbedding with other facies, mainly aeolian sandsheet and damp sandflat sandstones, suggests an environment that remained under the control of the palaeo-water table. Even at times, or in places, where aeolian processes were dominant at the palaeo-surface, the presence of a permanent water table in the near sub-surface would have limited the sand available for aeolian reworking and hence restricted the maximum size of dunes (cf. Fryberger *et al.* 1988). The distribution of those larger aeolian dune bedforms that are preserved accords with the suggestion that aeolian processes were largely dependent on a sand supply limited by the palaeo-water table.

Areas on and marginal to the Llyn-Rossendale Ridge preserve some of the largest aeolian dunes recorded in the Sherwood Sandstone Group with a particular dune complex encountered in and around the village of Frodsham being interpreted as part of a large sand mound or 'dome-shaped' dune (Thompson 1969). Such areas, including the margins of the East Irish Sea Basin and the extreme south of the Cheshire Basin, are likely to have been topographically higher than contemporaneous areas in a more basinal setting and therefore potentially subject to a relatively lower water table and, hence, greater sand availability. Palaeo-transport directions recorded from these areas reveal consistent easterly and south-easterly winds (Figure 3.28) that have been previously suggested to represent a low latitude trade wind influence (Thompson 1969) based on the position of Britain some 15-20°N at this time. Given more recent interpretations of Early Triassic climatic patterns (e.g. Parrish 1992) it seems more likely that the recorded wind directions represent a combination of cross-equatorial flow driven by the Pangaean monsoon and the trade wind effect driven by the earth's rotation. This may account for the southerly component in the recorded data whereas present-day low latitude northern hemisphere trade winds are dominantly north-easterlies.

Of particular note is the vertical association of sandflat, playa and aeolian facies where this can be recorded either in wells or suitable outcrops. It becomes apparent that in many instances the majority of the sandflat continuum are vertically juxtaposed such that, in an idealised section, sandstones representing aeolian dune facies are overlain by aeolian sandsheets that are in turn overlain by dry sandflats and then damp sandflat facies. An association such as this would appear to represent a changing relationship between the palaeo-surface and palaeo-water table through time with surficial conditions becoming progressively wetter through time. Conversely, the reverse association is equally commonly recorded and can therefore be regarded as representing an upward transition from wetter to drier conditions. Transitions such as these are recorded over vertical distances ranging from less than five metres to more than ten metres and are therefore best seen in the cores from wells rather than outcrops. Notwithstanding the limits of outcrop evidence, partial transitions of this type are recorded at Thurstaston Road Cutting (Figure 3.42), Moss Farm, New Brighton and Raw Head (see logs Appendix II). Neither are all

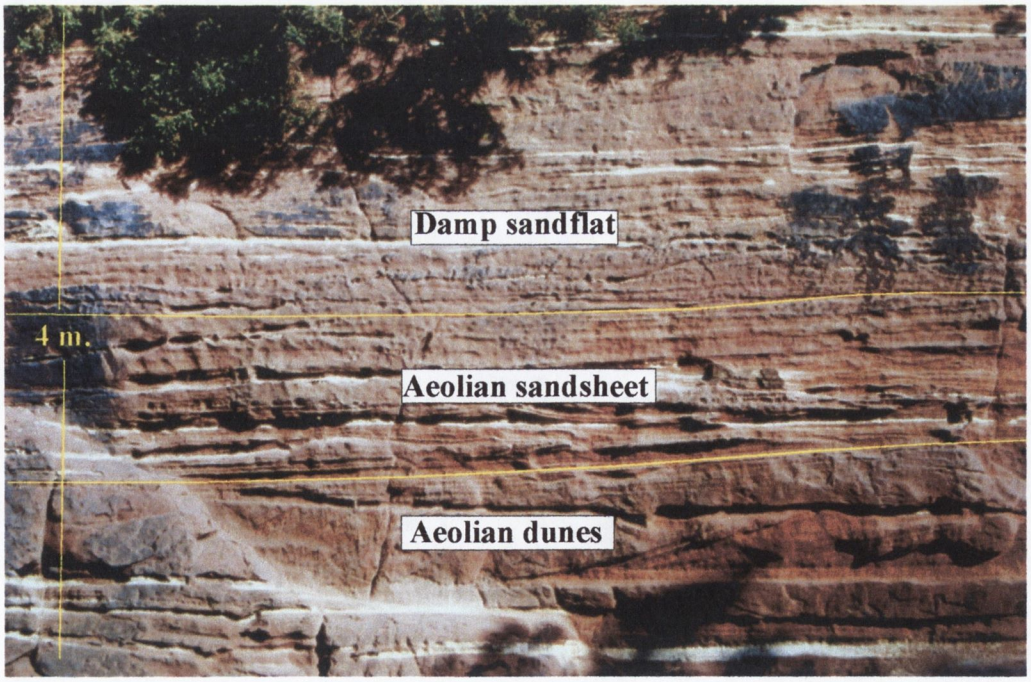


Figure 3.42 An upward wetting sequence indicated by the vertical association of aeolian dune, aeolian sandsheet and damp sandflat facies at Thurstaston Road Cutting, Wirral. This is the smallest order of climatically mediated cyclicity that can normally be detected from wireline logs in wells.

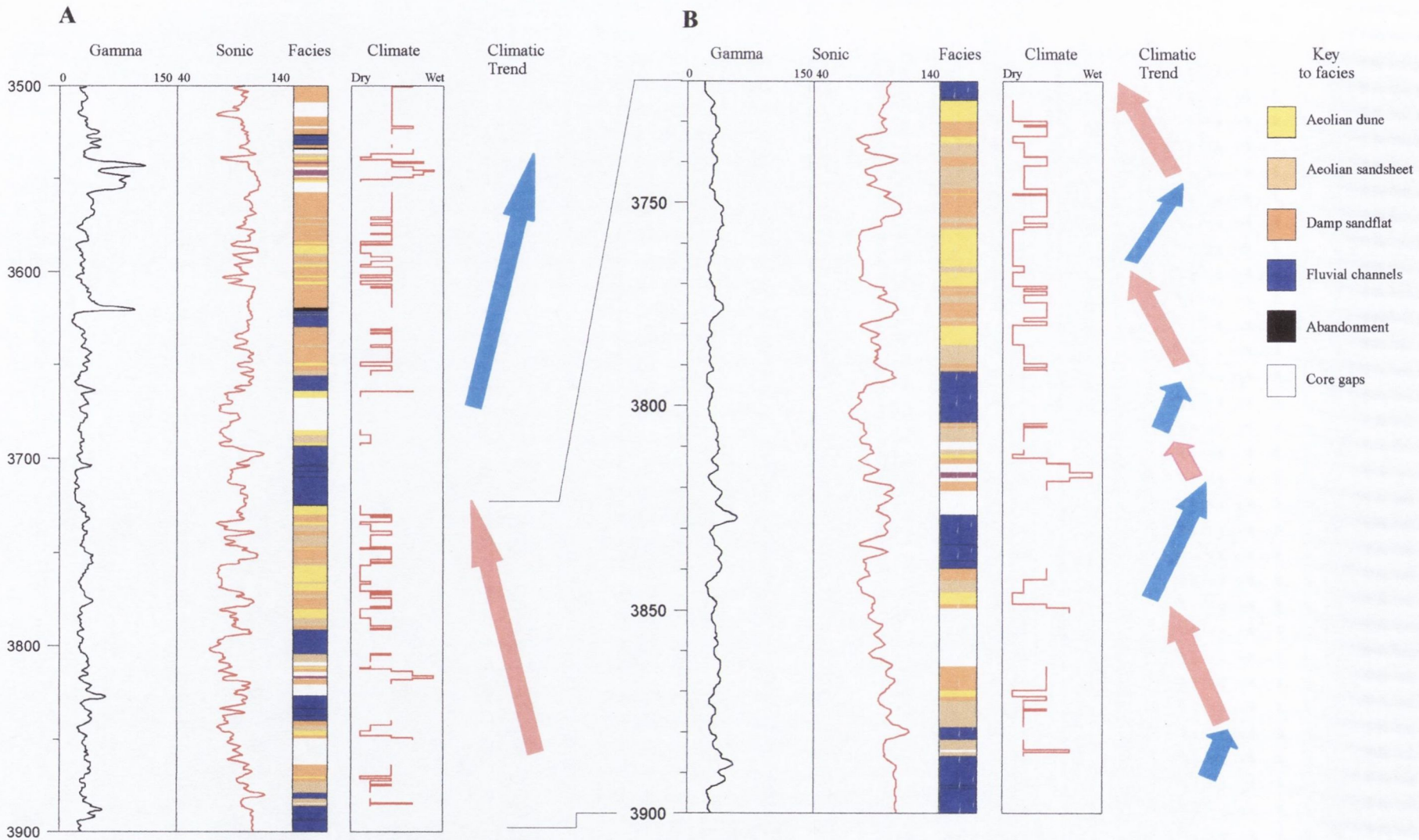


Figure 3.43 Sedimentary facies determined from core in well 110/2-6. The vertical distribution of aeolian, sandflat and playa facies reveals systematic variations on two scales that represent the relationship between the sediment surface and the palaeo-water table and reflect changing climate within the East Irish Sea Basin.

such transitions complete in terms of the facies present; they may range from damp sandflat to aeolian dune or from playa lake to damp sandflat but in both cases could be seen, in this instance, as representing as upward drying succession.

The best recorded vertical associations of sandflat and associated facies are found in the offshore wells where there are extensive cored intervals and in these the transitions can be seen to occur on at least two scales. Figure 3.43 illustrates the relationship from the lower parts of the cored interval in well 110/2-6, corresponding to part of the currently termed OS1 Member of the Ormskirk Sandstone Formation. The facies present, as well as being colour coded for ease of identification, are plotted on a linear scale with those facies representing wetter conditions, and by implication a relatively higher water table, to the right and those representing drier conditions, a relatively lower water table, to the left. It is clear from the gross interval depicted (A) that there are major upward drying and then upward wetting transitions recorded over the majority of the c.400 ft. shown. The detail (B), however, reveals smaller scale alternations present as part of the overall upward drying transition and these broadly conform in preserved thickness to those recorded in outcrops. It is also noticeable that, ignoring those fluvial channel sequences present in the interval shown (in blue), there is a correspondence between the facies and the sonic log character (as suggested by Meadows and Beach 1993a and discussed above in Section 2.3) that would enable the major changes in aeolian and sandflat facies to be identified outside the cored intervals.

The upward wetting and upward drying transitions recorded in both cores and outcrops are best interpreted as representing the changing relationship between the palaeo-water table and the coeval sediment surface. The regular nature of these transitions suggests a basin wide control on this relationship and is therefore most likely to reflect the prevailing climate within the basins under discussions. Although no time constraints can be placed on each wetting and drying transition, where best preserved as in the depicted cored interval from well 110/2-6, they are extremely cyclical in character. Additionally, their presence at two distinct scales would appear to indicate climatic controls on the water table operating over at least two time periods and may, inferentially, represent astronomical forcing as determined by Berger and Loutre (1994) and discussed by Blum and Törnqvist (2000). This aspect is discussed further below in Section 9.4.

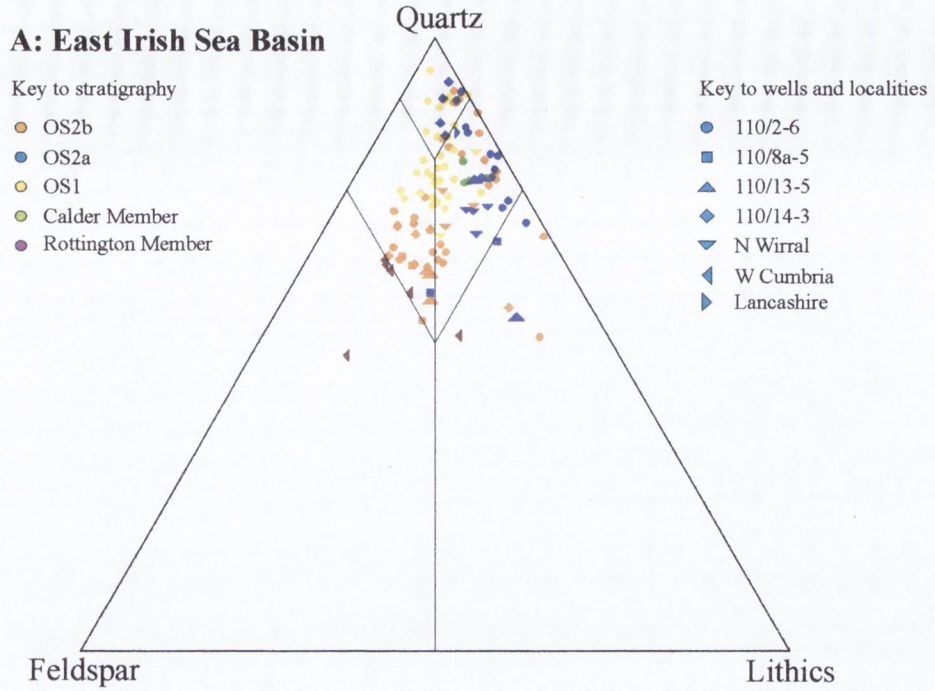
4. SHERWOOD SANDSTONE PETROGRAPHY

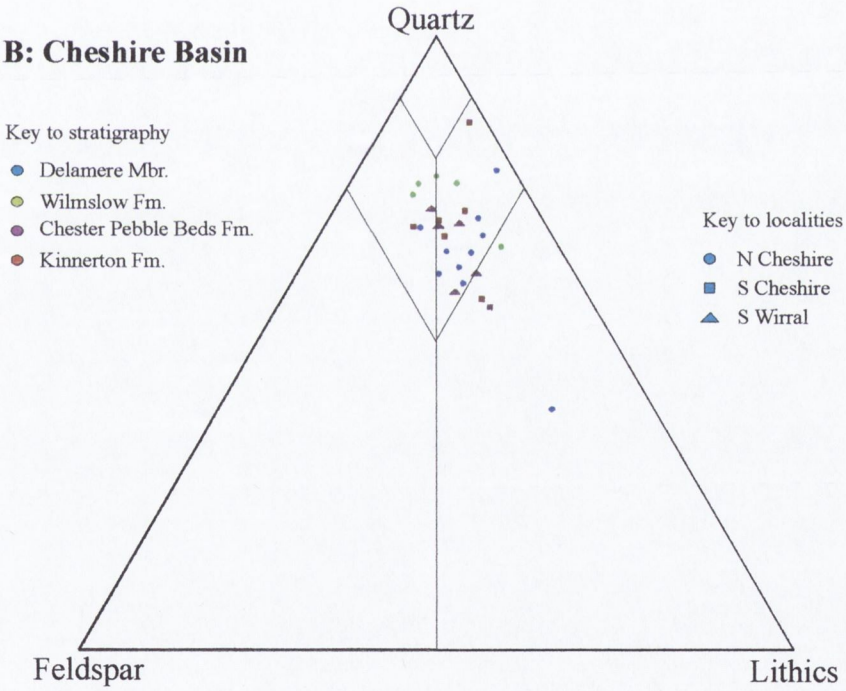
4.1 INTRODUCTION

A total of 141 thin section samples cut vertical to bedding have been examined using a Leitz Ortholux II POL-BK petrographic microscope with Wild MPS51 camera attachment and have undergone modal analysis using a Prior automated point count stage. This latter was set with incremental stage movements in excess of the maximum grain size in order to eliminate the possibility of counting the same grain twice. Modal data for each sample is based on a 200 point analysis and the resultant data is presented in Appendix III with the sandstone classification based upon corrected detrital proportions for each sample of quartz (including polycrystalline grains), feldspar and combined lithics including rock fragments, opaques and heavy minerals. The sandstones are classified using a scheme (Figure 4.1) modified from McBride (1963) and Dott (1964) that has been previously applied to Sherwood Sandstone Group samples (e.g. Greenwood and Habesch 1997) .

The use of 200 points for determining sandstone mineralogical composition follows the statistical examination of point count results by van der Plas and Tobi (1965) which indicates that for minerals comprising between 5-20% of the rock volume the 2σ error margin at 95% confidence varies from 3.0-5.5%. This range covers the measured values for feldspar, granitic and metamorphic rock fragments in the majority of the Sherwood Sandstone samples, the significance of which is discussed further below, and suggests that variations in the actual abundance of these grains is significantly greater than the statistical error margin. Critical testing of the van der Plas and Tobi (1965) chart by Howarth (1998) has amended these error values but, for the stated observed percentages and number of points, slightly reduces the error margins shown above. The point counts include both diagenetic phases and porosity where this is preserved within the samples as well as detrital components.

Additionally, the heavy mineral suite recorded in the sandstone samples from the four offshore wells logged for this study (110/2-6, 110/8a-5, 110/13-5 and 110/14-3) was counted separately to determine any variations in the abundance of mineral species. This involved recording the total number of each heavy mineral species encountered in each





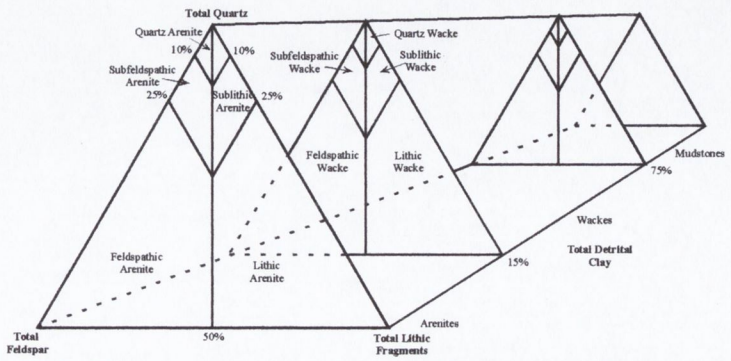


Figure 4.1 Comparative detrital mineralogies for all petrographic samples from the East Irish Sea and Cheshire Basins (classification scheme adapted from McBride 1963 and Dott 1964).

thin section, taking care that the total area of thin section over which the count was conducted was approximately the same for each sample.

4.2 DETRITAL MINERALOGY

The mean composition of the Sherwood Sandstone Group sandstones is that of a sublithic arenite (see Figure 4.1) but this bulk composition hides a considerable range of sandstone lithologies from quartz arenites to sublithic and subfeldspathic arenites (that form a considerable number of the samples) to rare lithic arenites and feldspathic arenites. Although there is considerable overlap of data points from specific stratigraphic units the East Irish Sea Basin data in Figure 4.1A reveal in particular variations in the feldspar content of the sandstones with those samples from the OS2a Member of the Ormskirk Sandstone and the Calder Member of the St Bees Sandstone being relatively feldspar poor, while those from the OS2b Member are relatively enriched. Samples from the OS1 Member of the Ormskirk Sandstone appear to be generally intermediate in feldspar content but the few available samples from the Rottington Member of the St Bees Sandstone are particularly rich in feldspar and include the only feldspathic arenites recorded in the entire data set. Samples from the Cheshire Basin (Figure 4.1B) reveal a less extensive spread of lithologies and appear to correspond most closely to many of those from the OS1 and OS2a Members in the East Irish Sea Basin with intermediate feldspar contents that place them dominantly as subfeldspathic and sublithic arenites. Given the stratigraphic dispersal of the Cheshire Basin samples, from the Kinnerton Sandstone through to the Delamere Member of the Helsby Sandstone, this is somewhat strange although it must be considered that the more limited sample numbers from the Cheshire Basin may have resulted in a biased data set.

Petrographic analysis has shown that there is a broad similarity in the types and mineralogies of detrital grains found in the Sherwood Sandstone Group samples from both the East Irish Sea and the Cheshire Basins. In general detrital grains fall into two main populations with a dominant grain type that ranges between very fine and medium sand grade and is subrounded to angular. The subordinate population comprises mainly medium to coarse sand grains that are rounded to very well rounded suggesting aeolian transportation. Where the two grain populations are found together, as commonly occurs in aeolian dune and sandsheet sandstones, this can lead to bimodal sorting (Figure 4.2)

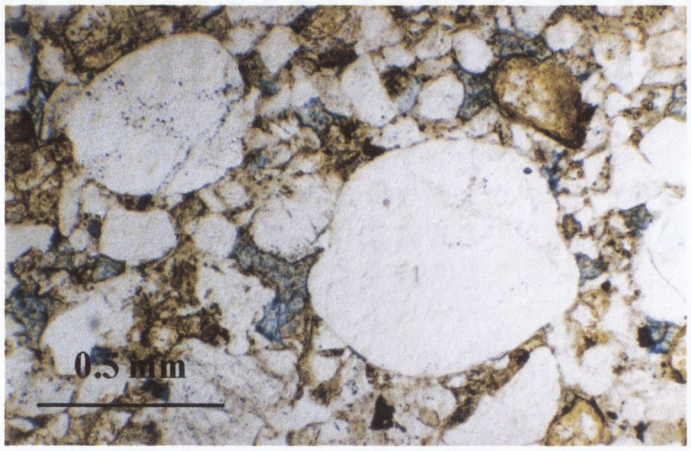


Figure 4.2 Well 110/14-3. Core depth 1100.00 m. General view in PPL of a bimodally sorted medium to coarse sandstone in aeolian sandsheet facies showing the presence of two grain populations

By far the most abundant constituent is quartz with slightly more than 50% of the total rock volume and 73% of the detrital component. The quartz grains can be subdivided into monocrystalline, equant polycrystalline, schistose polycrystalline and chert that form approximately 31%, 13%, 4% and 2% of the rock volume respectively. Monocrystalline quartz is generally unstrained to weakly strained and clear with few inclusions. Equant polycrystalline quartz grains appear generally to be equally clear with compromise boundaries between crystals (Figure 4.3). Quartz grains with a schistose fabric are distinct from the previously described grains, exhibiting a highly strained texture with a pronounced crystal orientation (Figure 4.4). Chert grains form a minor but ubiquitous component of the Sherwood Sandstone Group sandstones, are micro-crystalline and generally finer in grain size than the associated quartz and feldspar grains.

Feldspar grains are present in almost every sample, forming on average some 7.7% of the rock volume (maximum of 23% and minimum of 0%) and 11.4% of the detrital component. The assemblage is dominated by K-feldspar which comprises on average some 6.6% of the rock, while plagioclase grains comprise the remaining 1.1%. K-feldspar occurs as microcline, orthoclase and microperthite, the latter rarely exhibiting a runic texture indicative of a granitic, possibly pegmatitic, origin (Figure 4.6). Generally sparse plagioclase grains are only rarely twinned, suggesting an albitic composition, but are commonly rich in micro-inclusions. A minor proportion of the feldspar grains have undergone partial leaching with skeletal textures and the generation of secondary intragranular porosity.

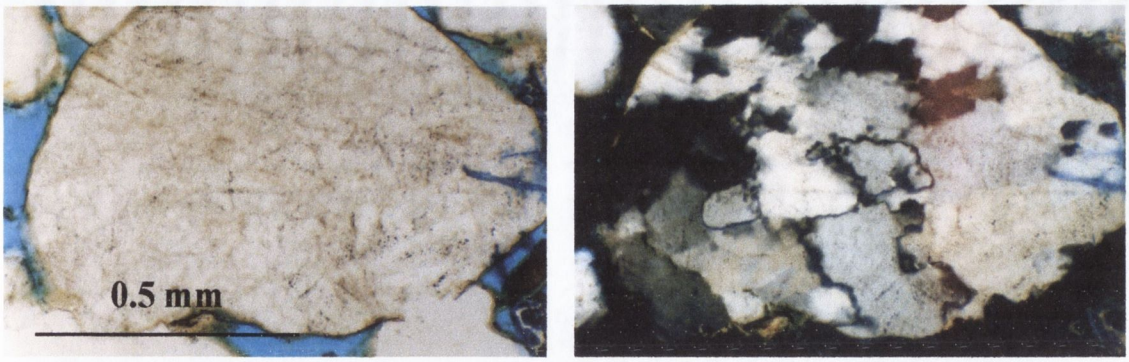


Figure 4.3 Unstrained polycrystalline quartz grain with an equant sub-grain fabric (PPL to the left, XN to the right).

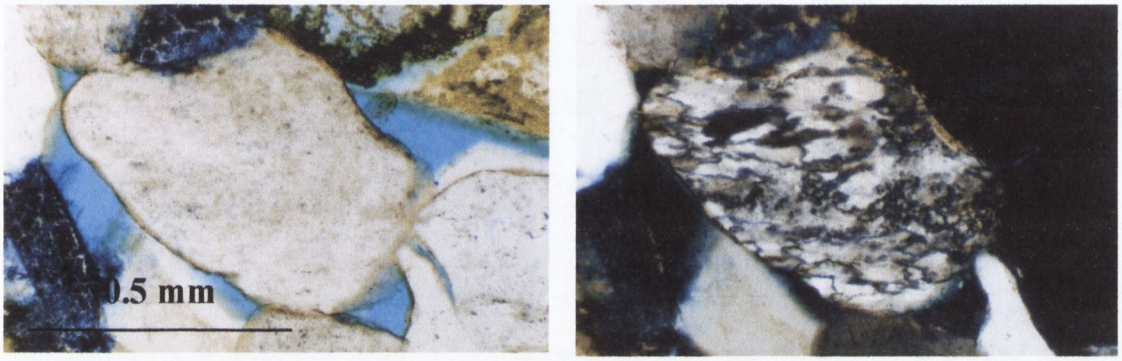


Figure 4.4 Polycrystalline quartz grain with a schistose fabric (PPL to the right, XN to the left).

Mica is a sparse (less than 0.5% of the rock volume on average) and somewhat variable constituent of the sandstones, the most common variety being muscovite with rare biotite and chlorite. Micas are locally degraded to kaolinite and illite and tend to be compactionally deformed.

Rock fragments, comprising grains that have either multiple mineral constituents or are identifiable reworked sedimentary clasts, form more than 10% of the rock volume although their overall abundance is highly variable and can in part be directly related to the mean grain size of a sample as larger grains have a greater chance of having a compound mineralogy. Rock fragments identified within the Sherwood Sandstone Group sandstones fall into five distinct categories comprising granitic, metamorphic and volcanic grains, sedimentary intraclasts and fragments of reworked caliche. The stratigraphic and areal distribution of the various rock fragment types is discussed further below in Section 4.4. Granitic grains comprise quartz and feldspar, mainly K-feldspar, with rare muscovite mica

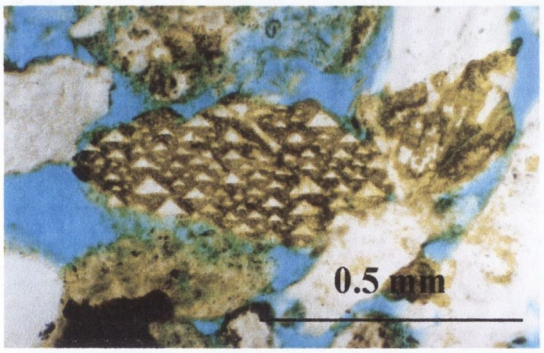


Figure 4.5 K-Feldspar grain with inter-grown quartz exhibiting a runic fabric.

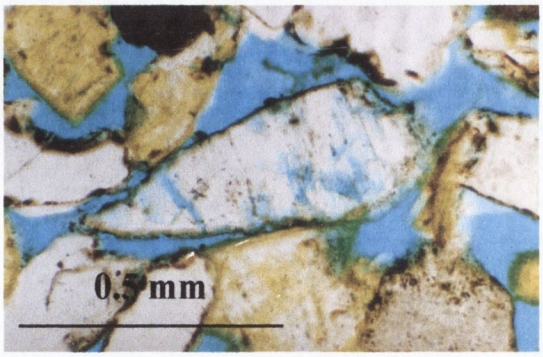


Figure 4.6 Plagioclase feldspar grain that has undergone partial dissolution.

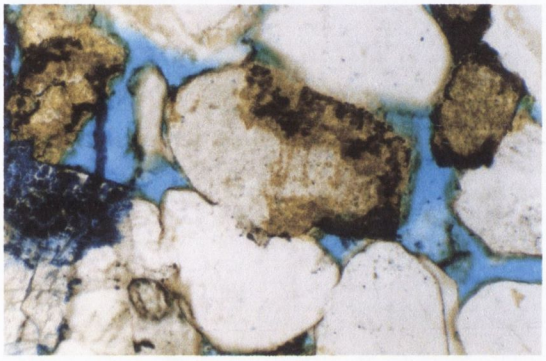
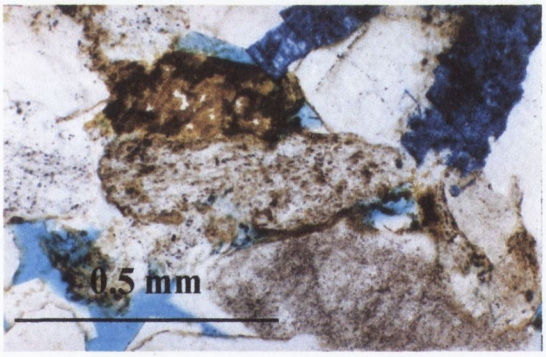


Figure 4.7 Compound quartz and feldspar grain with an equant fabric suggesting a granitic derivation.



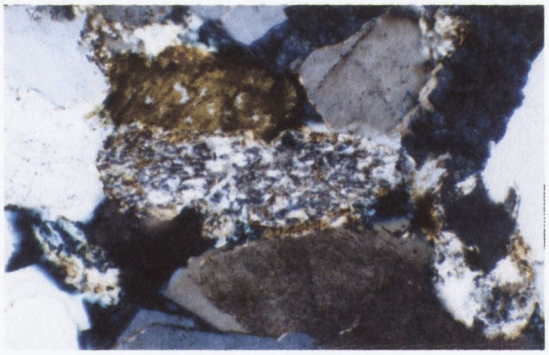
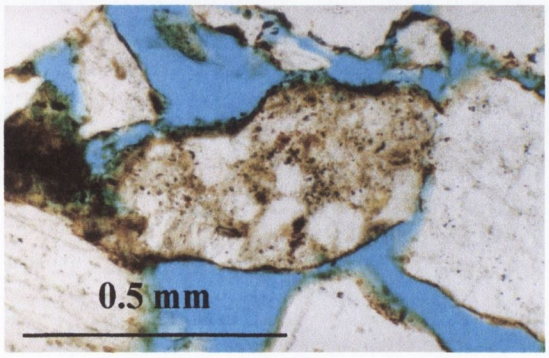


Figure 4.8 Rock fragment comprising quartz, feldspar and mica and exhibiting a highly schistose fabric suggesting a metamorphic derivation.



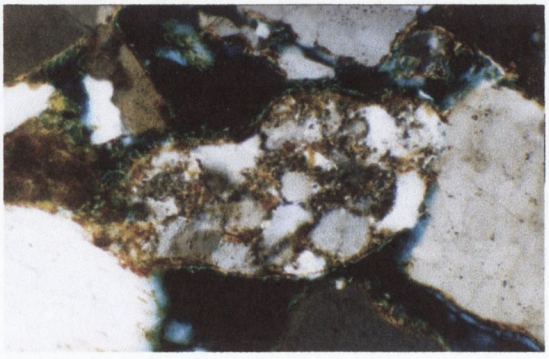


Figure 4.9 Rock fragment comprising very fine sandstone with an illitised clay matrix suggesting derivation from a low grade metamorphic hinterland

and exhibit an equant fabric similar to that of the equant polycrystalline quartz grains (figure 4.7). By comparison, metamorphic grains range from highly schistose mica-rich grains with fine sheared quartz and K-feldspar crystals (Figure 4.8) to low grade metamorphosed sandstones in which discrete constituent grains can be identified together with an illitised or more commonly chloritised matrix (Figure 4.9). Granitic and metamorphic grains are by far the most common rock fragments in the majority of samples, forming on average 4.4% and 4.7% respectively. Sparse volcanic grains exhibit a highly altered and very finely crystalline texture (Figure 4.10) with, in some instances, remnant traces of glass shards and fine feldspar phenocrysts.

Intra-formational sedimentary clasts include claystone and siltstone particles that vary from sand grade clasts through, in outcrop, to rip-up clasts several 10's cms in length. These clasts are common throughout the Sherwood Sandstone Group and are invariably recorded within the bases of fluvial channel sandstones or scattered along foreset surfaces as described in Section 3.2.1. They can be related to the syn-sedimentary reworking of previously deposited fines material within the channel systems and provide evidence for partial to at times complete abandonment of channel anabranches. By contrast, sandstone intraclasts are relatively sparse and are recorded most commonly, and specifically, within the basal fluvial channel sandstone of the Delamere Member of the Helsby Sandstone Formation (see Sedimentary Logs for Carden Park, Helsby Hill and Raw Head). In many instances the sedimentary structure of the sandstone clasts can be directly related to underlying facies from which they were presumably eroded and reworked.

Also sedimentary in origin are carbonate spheroids, referred to as caliche fragments in the modal analysis tables (Appendix III), that comprise concentric spheroidal structures of calcite, or rarely dolomite, with a radial fibrous texture (Figure 4.11). The concentric banding of the spheroids is clearly visible in most due to darker bands that are presumed to represent increased clay content within the spheroid. The formation of the spheroids has been examined and discussed by Strong and Pearce (1995) who, while remaining somewhat ambivalent on the processes involved, relate their occurrence to pedogenesis and the possible generation of groundwater nodules during caliche formation. Whether the spheroids recorded during the present study are *in situ* or reworked is unclear although the

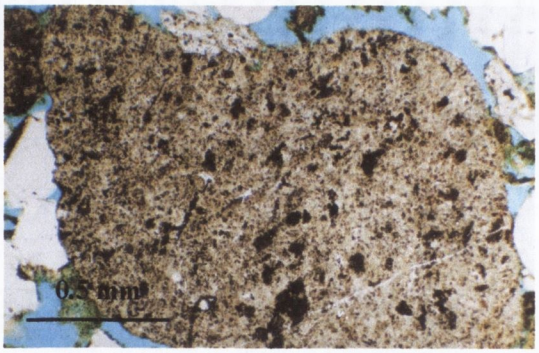


Figure 4.10 Highly altered volcanic grain with glass shards set in a finely crystalline groundmass (PPL).

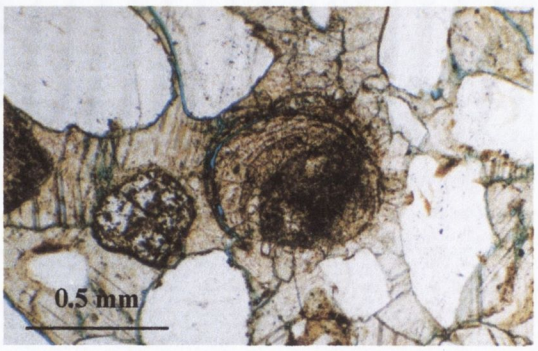


Figure 4.11 Remnant caliche fragment with radial fabric, partially replaced by non-ferroan calcite (PPL).

majority appear to form a part of the rock fabric, suggesting reworking and incorporation during deposition.

Generally trace amounts of detrital opaques, presumed to be haematite, magnetite or ilmenite, and heavy minerals occur throughout the Sherwood Sandstone Group. The heavy mineral suite is dominated by zircon, apatite and tourmaline, the latter as brown, blue and green varieties (Figure 4.12a, 12b and 12c) with minor quantities of rutile and monazite and rare occurrences of pyroxene. Also recorded from the Sherwood Sandstone Group, but not seen during the present study, are garnet, staurolite and chrome spinel (Mange *et al.* 1999). It is of particular note that the overall abundance of heavy minerals varies significantly through the stratigraphy, although this is only really apparent where core is available in well sections, and it was in response to this observation that a count was made of different heavy mineral species in the four cored and sampled wells (see Appendix III and discussion below in Sections 4.4 and 5.4). Rare occurrences of organic remains are also recorded, mainly in the form of highly altered phosphatic particles that are presumed to be bone fragments (Figure 4.13).

Non-resolvable clays, so termed because they are beyond the resolution of optical petrography, form a highly variable but ubiquitous component of the sandstones. They generally occur as thin grain rimming coatings, but can locally form pore-filling complexes, that are light brown to green in colour and apparently structureless. Such clays are presumed to be infiltrated, either from wind-blown dust or through downward percolating porewaters, but can provide the substrate for later clay authigenesis in the form

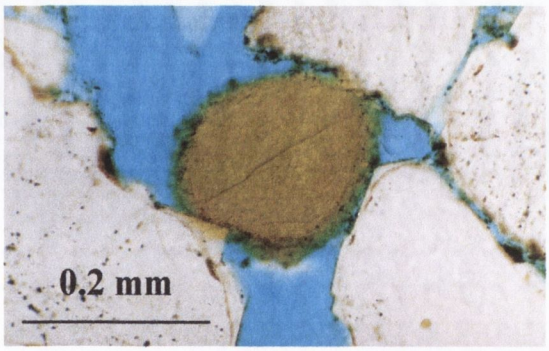


Figure 4.12a Brown tourmaline, the most abundant heavy mineral in the Sherwood Sandstone Group (PPL).

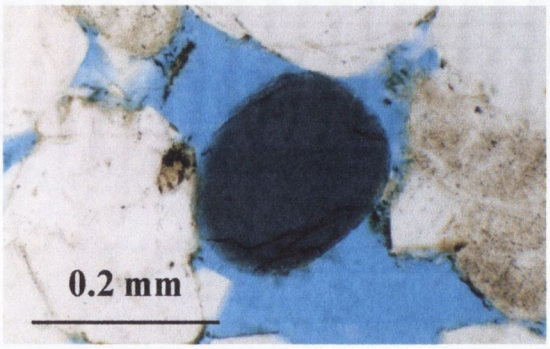


Figure 4.12b Blue tourmaline (PPL).

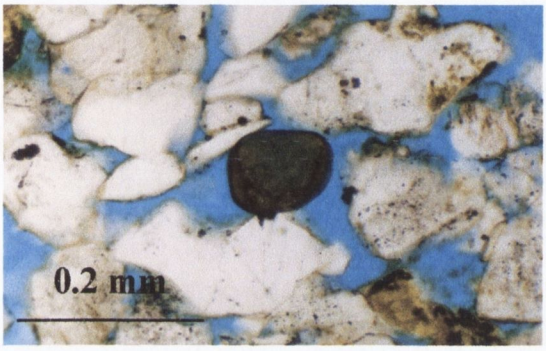


Figure 4.12c Green tourmaline (PPL).

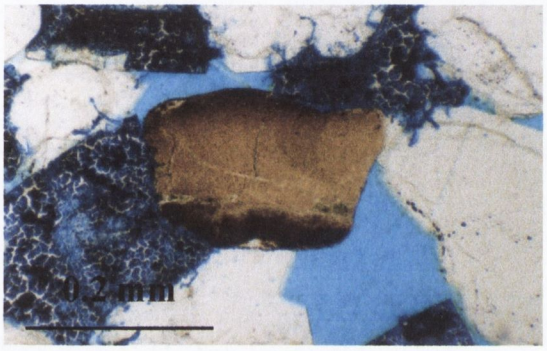


Figure 4.13 Phosphatic grain probably altered from a bone fragment (PPL).

of illite or chlorite. Where at their most abundant (≥10%) they occur as discrete laminae as well as being pore filling and are more likely to be detrital in origin.

4.3 AUTHIGENIC MINERALOGY

The diagenesis of the Sherwood Sandstone Group is of little concern in the present study except in so far as the presence of cement phases impacts on the whole rock geochemistry of the sandstones (see Section 5).

Blocky cement phases include calcite, dolomite (both non-ferroan and ferroan), gypsum/anhydrite, quartz and haematite with trace amounts of K-feldspar, plagioclase, pyrite and anatase. Of these the quartz and the non-ferroan dolomite are by far the most abundant, recording on average nearly 5% and nearly 4% of the rock volume respectively. Authigenic quartz occurs predominantly as syntaxial overgrowths on both monocrystalline and polycrystalline quartz grains, in many cases forming well developed euhedral crystal growths with, in some instances, compromise boundaries where overgrowths developed on adjacent grains have coalesced (Figure 4.14). There is, however, a very significant

dichotomy in the distribution of authigenic quartz in that fluvial channel sandstones contain higher percentages than non-channelised facies such as sandflats, aeolian sandsheets and dunes. This apparent facies control on the abundance of quartz cement has been noted and discussed by Meadows and Beach (1993b) who record modes for authigenic quartz as less than 4% in aeolian and sandflat facies compared to 8-12% in fluvial facies and by Greenwood and Habesch (1997) who record mean abundances of 1.5% for aeolian, 1.9% for sandflat and 5.5% for fluvial sandstones. Various models for explaining the facies discrepancy in quartz abundance have been proposed including early evaporite cements, now removed, within the aeolian and sandflat facies (Stuart and Cowan 1991; Cowan 1993) and differences in textural maturity (Meadows and Beach 1993b) although these remain unresolved. Whatever the reasons for the distribution of the quartz cement, its preference for fluvial channel sandstones does result in significantly different porosity characteristics between the facies that are recorded in wireline log responses (particularly density and sonic logs) and can therefore be used to differentiate facies in the absence of core (Meadows and Beach 1993a) as discussed in Section 2.3. This aspect of the sandstones may also account for the relative hardness of fluvial channel sandstones that results in their forming the cap to the vast majority of the Sherwood Sandstone hills in the Cheshire Basin and the highly resistant coastal cliffs of west Cumbria.

Non-ferroan dolomite occurs in two habits; an early form that is microcrystalline and pore filling, which is associated almost entirely with the clastic sabkha facies and is therefore presumably syn-sedimentary, and a later form that comprises subhedral to euhedral rhombs that have been related to the onset of burial diagenesis (Greenwood and Habesch 1997). In the majority of cases the non-ferroan dolomite crystals form the cores of larger ferroan

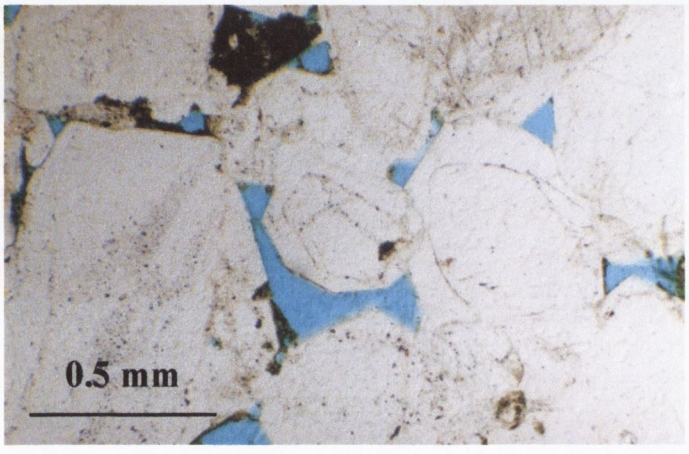


Figure 4.14
Tightly quartz cemented fluvial sandstone from Beeston Hill. Well developed syntaxial overgrowths exhibit compromise boundaries and reduce porosity (PPL).

dolomites that are locally pore filling, the change to a ferroan chemistry being associated with increasing pressure and temperature and the migration of early hydrocarbons into the reservoir (Stuart and Cowan 1991; Greenwood and Habesch 1997). Calcite cements occur sporadically and are generally closely associated with the calcite spheroids, on which they form blocky subhedral overgrowths.

Other subordinate phases include gypsum/anhydrite which occurs as a late stage blocky cement in the form of pore filling euhedral crystals and crystal aggregates, K-feldspar as sparse epitaxial overgrowths on K-feldspar grains and haematite as thin grain coatings, rare crystal aggregates and as a clay replacement phase. Each of these cements occurs in average abundances of around 0.3-0.6% of the rock volume, and are hence relatively insignificant in terms of whole rock geochemistry, although maximum values for haematite of 5.5-7.0 in the basal Sherwood Sandstone Group succession in west Cumbria would locally be sufficient to generate an Fe anomaly. Additionally, in well 110/8a-5, anhydrite is locally much more abundant but occurs as a primary precipitate in the form of laminae and nodules, locally disrupted, comprising felted lath-like crystals (Figure 4.15) that have been ascribed to clastic sabkha conditions (Thompson and Meadows 1997). In addition to the phases discussed there are trace amounts of pyrite, authigenic plagioclase and anatase.

The major authigenic clay phases recorded are illite and kaolinite with rare and trace amounts of chlorite, the latter only being recorded in the upper parts of the cored interval in well 110/2-6 as a grain rimming phase and at Alberbury in the extreme south of the Cheshire Basin as a clay replacement phase. Kaolinite occurs mainly as a replacement phase after feldspars and mica, in which case it forms short vermicular stacks of platelets, and as locally pore-filling complexes but is never sufficiently abundant that it has a significant effect on whole rock geochemistry. By comparison, illite is widespread throughout the sandstones, but is significantly more abundant in well 110/2-6 in the Morecambe Field than in any of the other wells. Illite comprises an average of nearly 4% of the rock volume across all samples but more than 6% in well 110/2-6 with a significant number of samples recording in excess of 10% and a maximum of 16% (well 110/2-6, core depth 981.50m). The standard chemical composition of illite ($KAl_4[Si_7AlO_{20}][OH]_4$) implies that these abundances may significantly effect whole rock geochemistry, especially with respect to K_2O (see discussion below in Section 5.2), and that the distribution of illite

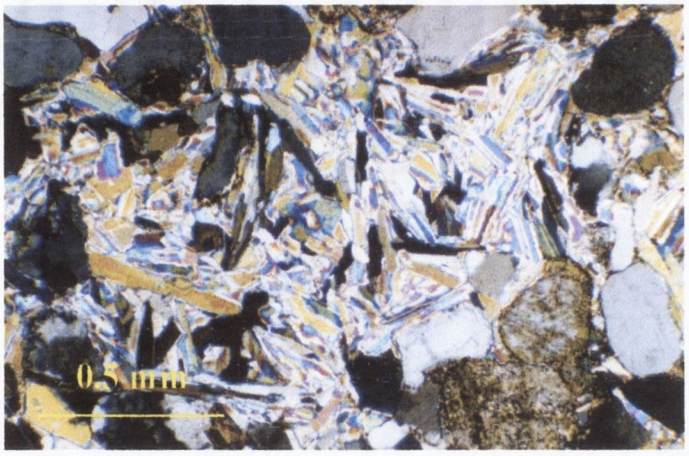


Figure 4.15
Well 110/8a-5
Core depth 1246.72 m.
Primary anhydrite within sandstones from a clastic sabkha sequence exhibiting a typical felted-lath fabric (XN).

would therefore need to be taken into account in any interpretation of major oxide data. The presence and stratigraphic distribution of illite in the Morecambe Field (including well 110/2-6) has been discussed at length in several publications (e.g. Bushell 1986; Macchi *et al.* 1991; Woodward and Curtis 1987) with the general consensus that the main phase of illite authigenesis post-dates an early hydrocarbon charge in this field, leading to a 'top platy illite' surface below which illite abundances increase dramatically.

4.4 STRATIGRAPHIC DISTRIBUTION

The stratigraphic position of many outcrops, particularly those presumed to lie within the Ormskirk and Helsby Sandstone Formations, is somewhat equivocal to say the least and, hence, the cored well sections provide the best opportunity to identify any vertical variations in the mineralogical assemblage within the upper parts of the Sherwood Sandstone Group. In particular, the extensive thin section database available from well 110/2-6 includes a total of 71 samples running through the Ormskirk Sandstone Formation from within two metres of the contact with the Mercia Mudstone Group to, and below, the base of the formation into the top of the Calder Member of the St Bees Sandstone Formation. These data are supplemented by more sparse datasets from wells 110/8a-5 (5 samples), 110/13-5 (6 samples) and 110/14-3 (11 samples), the core samples in the latter well latter being augmented by five sidewall core samples from below the cored interval. Only sparse data is available from the Calder Sandstone Member/Wilmslow Sandstone Formation either offshore or onshore, while the outcrops in west Cumbria plus those at

Burton Point and Bromborough Beach provide data on the Rottington Sandstone Member/Chester Pebble Beds Formation.

The petrographic data from well 110/2-6 reveals potentially stratigraphic variations in the modal compositions of the Ormskirk Sandstone Formation sandstones (Figure 4.16), in which the upper parts of the formation appear to be enriched in feldspar and to a lesser extent in chert but depleted in quartz, especially monocrystalline quartz, and metamorphic rock fragments above approximately 3200ft. The lower parts of the formation are somewhat similar and are particularly notable for the downward increase in feldspar, especially K-feldspar, below approximately 3500ft. By comparison, the intervening interval forming the middle part of the Ormskirk Sandstone Formation is significantly depleted in feldspar but appears to be relatively enriched in quartz.

In addition to the raw modal data, Figure 4.16 shows a GMi track that is calculated from the percentages of granitic and metamorphic rock fragments using the equation GMi=(Granitic fragments x 100)/(Granitic fragments + Metamorphic fragments). In this calculation the granitic fragments are taken to be the sum of granitic rock fragments (as counted in the modal analysis tables, Appendix III) and equant polycrystalline quartz grains. Similarly, the metamorphic fragments comprise the sum of metamorphic rock fragments and schistose polycrystalline quartz grains. Generating a ratio of the two major rock fragment types negates any inherent difficulties with the raw modal data induced by variations in grain size or through hydraulic sorting of grains and follows standard data interpretation practices for heavy mineral suites (Morton and Hurst 1995). Plots of the GMi should therefore reveal any subtle differences in the provenance of the sandstones that have influenced the relative proportions of granitic and metamorphic grain types. In well 110/2-6 several changes in the GMi are apparent through the Ormskirk Sandstone Formation, in some instances correlating with changes in the abundance of either feldspar or quartz.

The same plots for wells 110/8a-5 (Figure 4.17), 110/13-5 (Figure 4.18) and 110/14-3 (Figure 4.19), although based on a considerably more limited sample number, do reveal similar trends. In particular, the upward increase in total feldspar (consequent mainly on the abundance of K-feldspar) is apparent in all three wells at depths of approximately

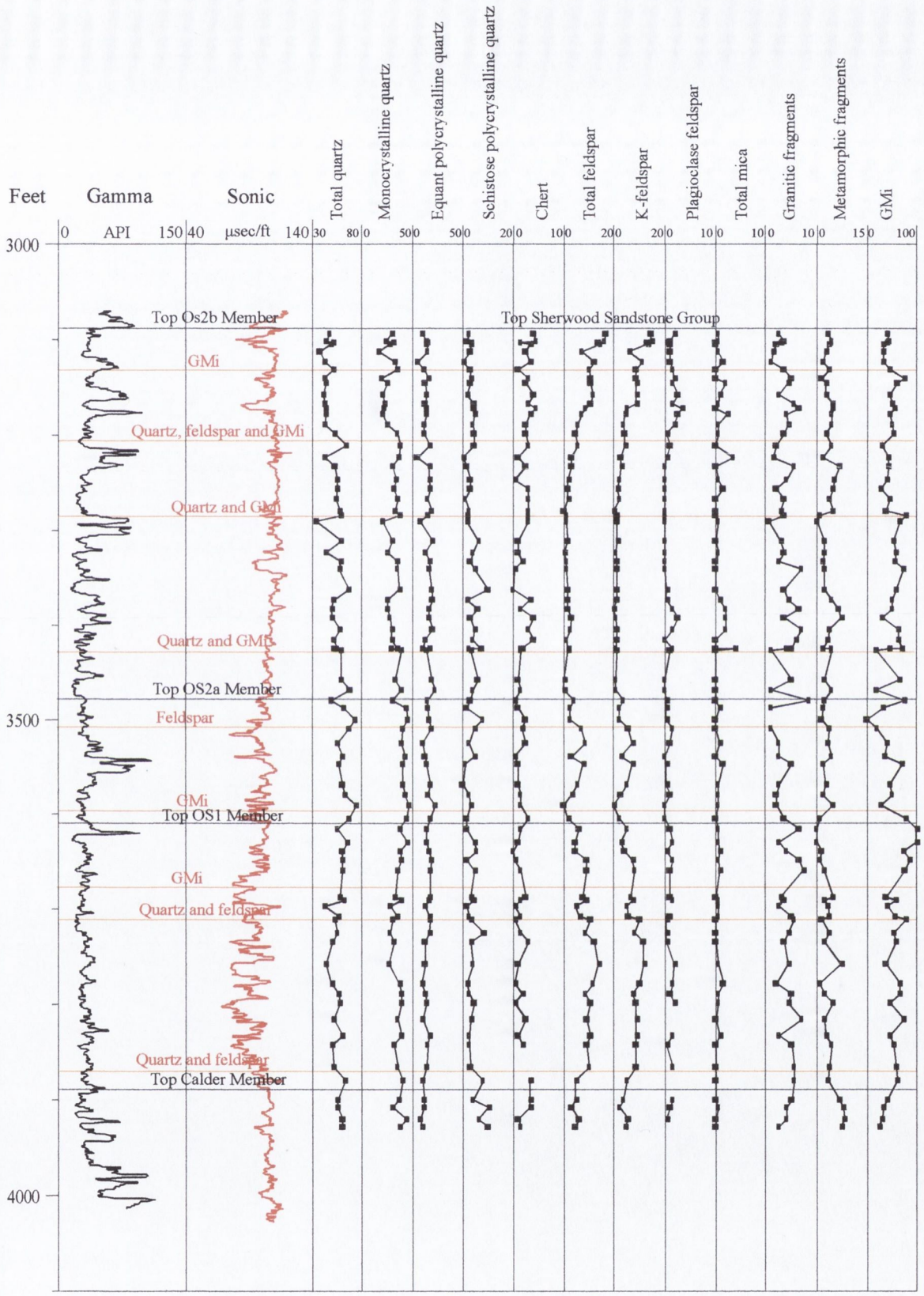


Figure 4.16 Modal analysis data for samples from well 110/2-6 plotted through the Ormskirk Sandstone Formation. Current stratigraphy shown in black and suggested petrographic picks in red

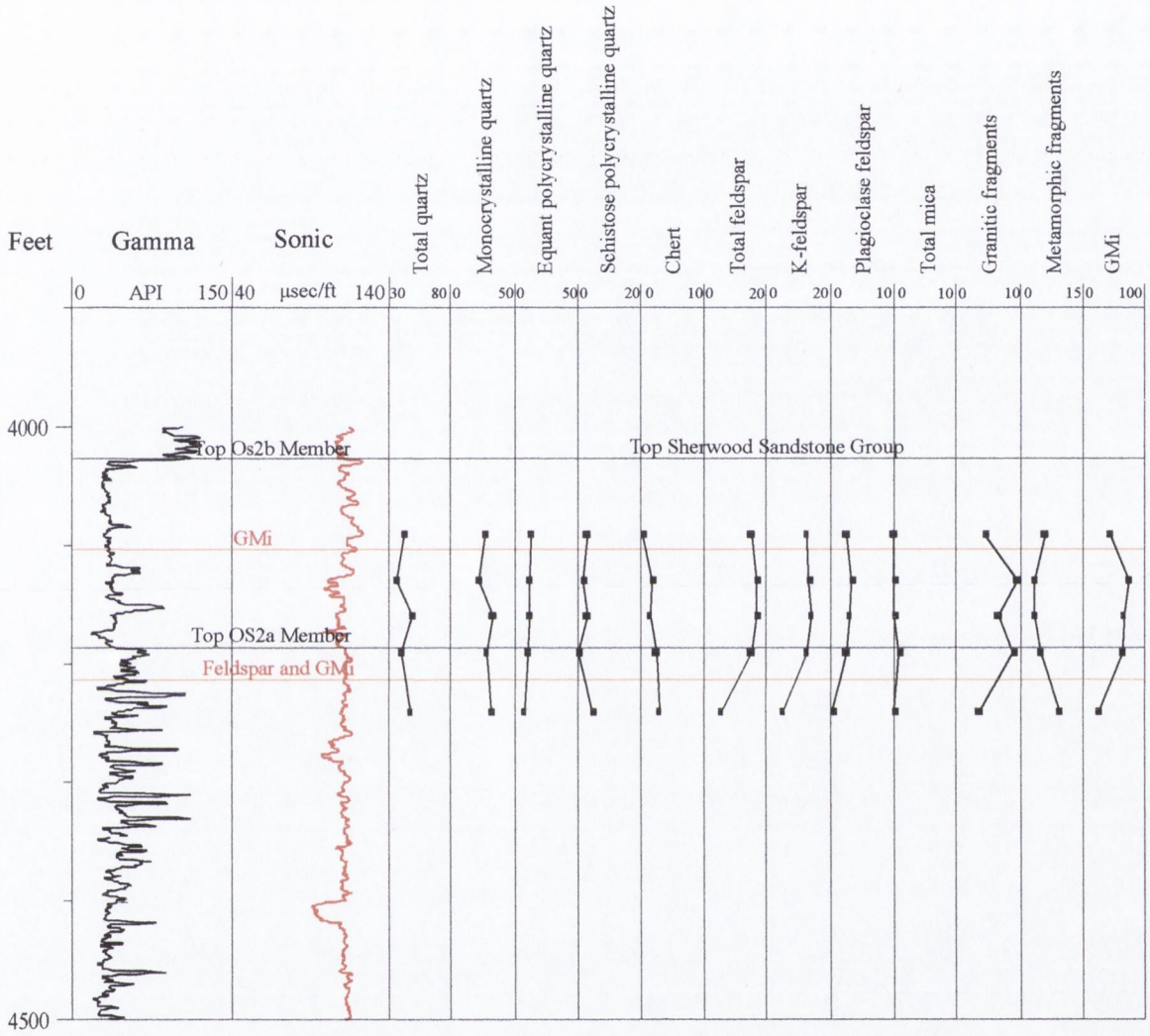


Figure 4.17 Modal analysis data for samples from well 110/8a-5 plotted through the upper part of the Ormskirk Sandstone Formation. Current stratigraphy shown in black and suggested petrographic picks in red.

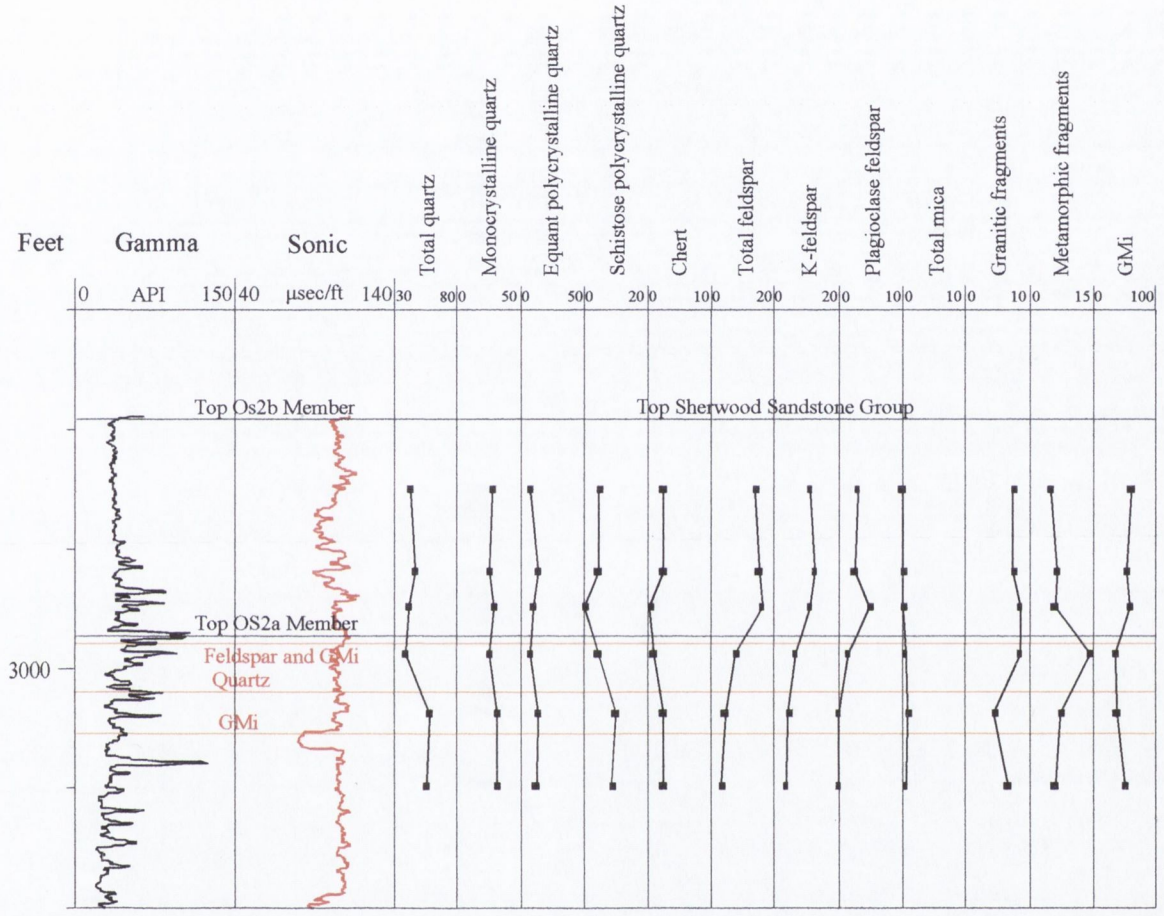


Figure 4.18 Modal analysis data for samples from well 110/13-5 plotted through the upper part of the Ormskirk Sandstone Formation. Current stratigraphy shown in black and suggested petrographic picks in red

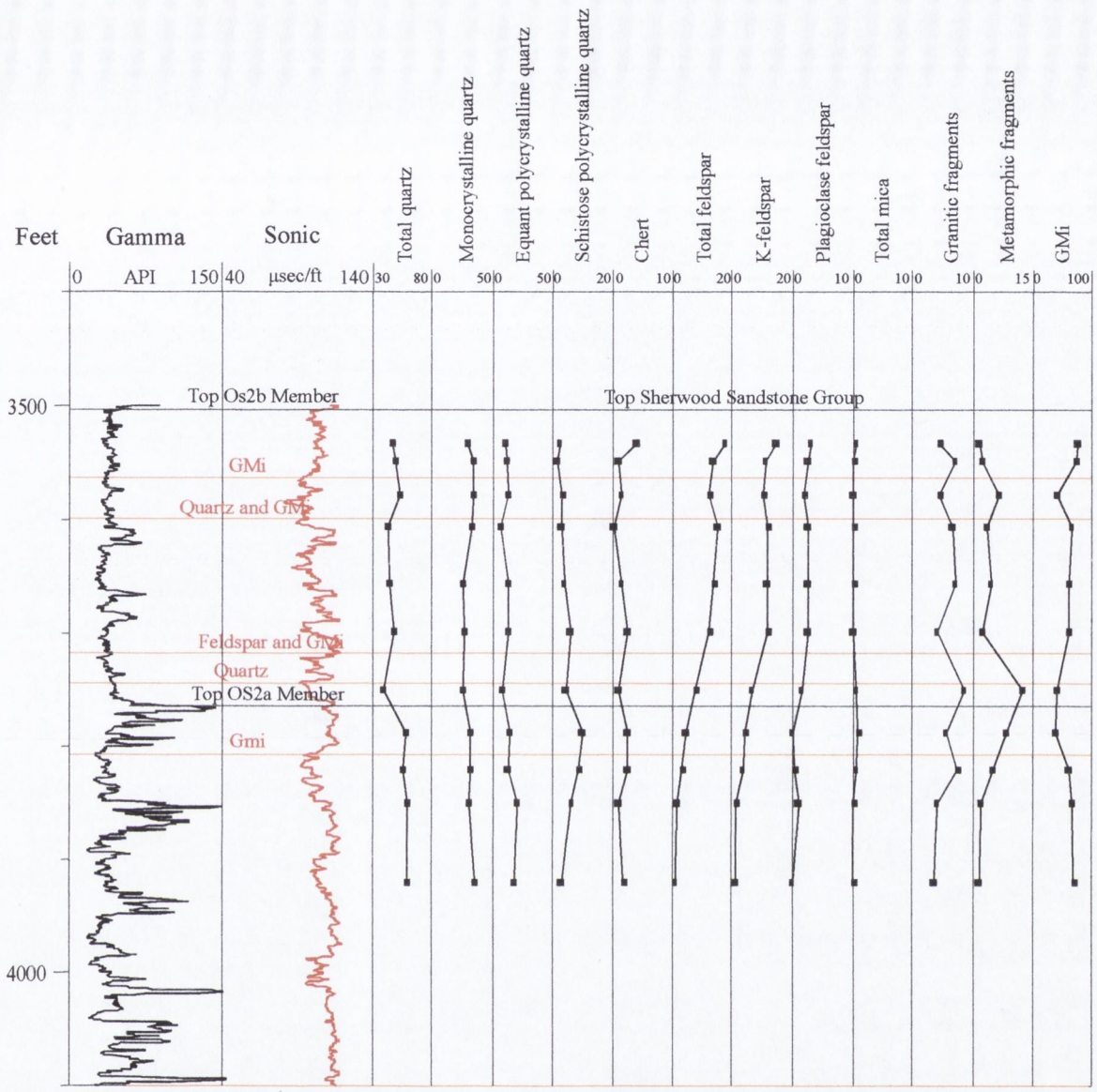


Figure 4.19 Modal analysis data for samples from well 110/14-3 plotted through the upper part of the Ormskirk Sandstone Formation. Current stratigraphy shown in black and suggested petrographic picks in red.

4200ft, 2980ft and 3720ft respectively. As in the case of well 110/2-6 this increase in feldspar is closely associated in all wells with a equivalent upward increase in the GMi which appears from the modal data to mainly reflect an increase in the abundance of granitic rock fragments. Only in well 110/14-3 is there an upward decrease in the raw modal data for granitic fragments although the commensurate decrease in metamorphic fragments is somewhat greater, resulting in the increased GMi, and may therefore be due to a grain size change. It is also apparent that the stratigraphic variations in detrital mineralogy have little or no correlation to the existing lithostratigraphy which is also shown on Figures 4.16-4.19. The upward increases in total feldspar and GMi, for example, are almost coincident with the top of the OS2a Member in well 110/13-5 but are some distance below this pick in wells 110/8a-5 and 110/14-3 and nearly 300ft above it in well 110/2-6. If the variations in detrital mineralogy have any stratigraphic implications (discussed further in Sections 6) then it becomes clear that there is a major discrepancy with the currently accepted lithostratigraphy.

Similar differentiation in the Cheshire Basin samples is difficult to ascertain, in part due to the paucity of samples from the corresponding Frodsham and Thurstaston Sandstone Members, but Delamere Sandstone Member samples appear to be significantly more feldspathic than their OS2a Member equivalents in the East Irish Sea Basin (Figure 4.2). Wilmslow Sandstone Formation samples are also more feldspathic than those from the Calder Sandstone Member, while samples from the Chester Pebble Beds Formation appear to be slightly less feldspathic than their equivalents in the Rottington Sandstone Member where sampled in west Cumbria. There is in fact little distinction with respect to feldspar content between the formations in the Cheshire Basin although this may be more a function of uncertainty regarding the stratigraphy, including the position or even existence of the Thurstaston Sandstone Member, than sampling bias.

There are, however, some subtle differences in the lithic content of the sandstones that may have stratigraphic implications. In particular, it appears that the Delamere Sandstone Member samples are generally more lithic-rich than others, while those few samples available from the Wilmslow Sandstone Formation appear to be somewhat lithic-poor. Examination of the modal analysis tables reveals that the variations in the lithic component are mainly a function of changes in the abundance of metamorphic rock fragments which

would therefore impact the calculated GMi and may provide a means of establishing a tentative correlation between the Cheshire and the East Irish Sea Basins.

There also appears to be some stratigraphic significance to variations in the abundance of heavy minerals within the Ormskirk Sandstone Formation as determined from heavy mineral counts based on thin section data. Whilst it is acknowledged that this method of determining heavy mineral numbers is less accurate than the rigorous separation methods advocated by specialists (e.g. Morton and Berge 1995; Mange-Rajetzky 1995) it nonetheless does serve to highlight significant changes in the abundance of heavy minerals through the succession. The data from well 110/2-6 (Figure 4.20) reveals a total of 12 horizons through the Ormskirk Sandstone Formation where there appear to be increases somewhat above the background level that effect several heavy mineral species. These are most notable for the zircon, apatite and tourmaline grains and, to a lesser extent, for monazite but some are also noticeable in the count of opaques minerals.

Although the heavy mineral data is sparse for the other three wells they do reveal similar variations (Figures 4.21, 4.22 and 4.23) with corresponding increases in zircon and apatite in particular. While it is clear that the heavy mineral counts in this form and on their own do not constitute a valid method of correlating between wells, they may reflect stratigraphically significant influxes of sand rich in these minerals and hence add useful corroborating data to correlations based upon more rigorous methods. It is notable that the horizons within which the increases are recorded cover the entire spectrum of sedimentary facies with nine lying within fluvial channel sandstones, six within sandflats and six within aeolian sandstones. It seems reasonable therefore to presume that the concentrations of heavy minerals are not a function of hydraulic sorting by either fluvial or aeolian processes.

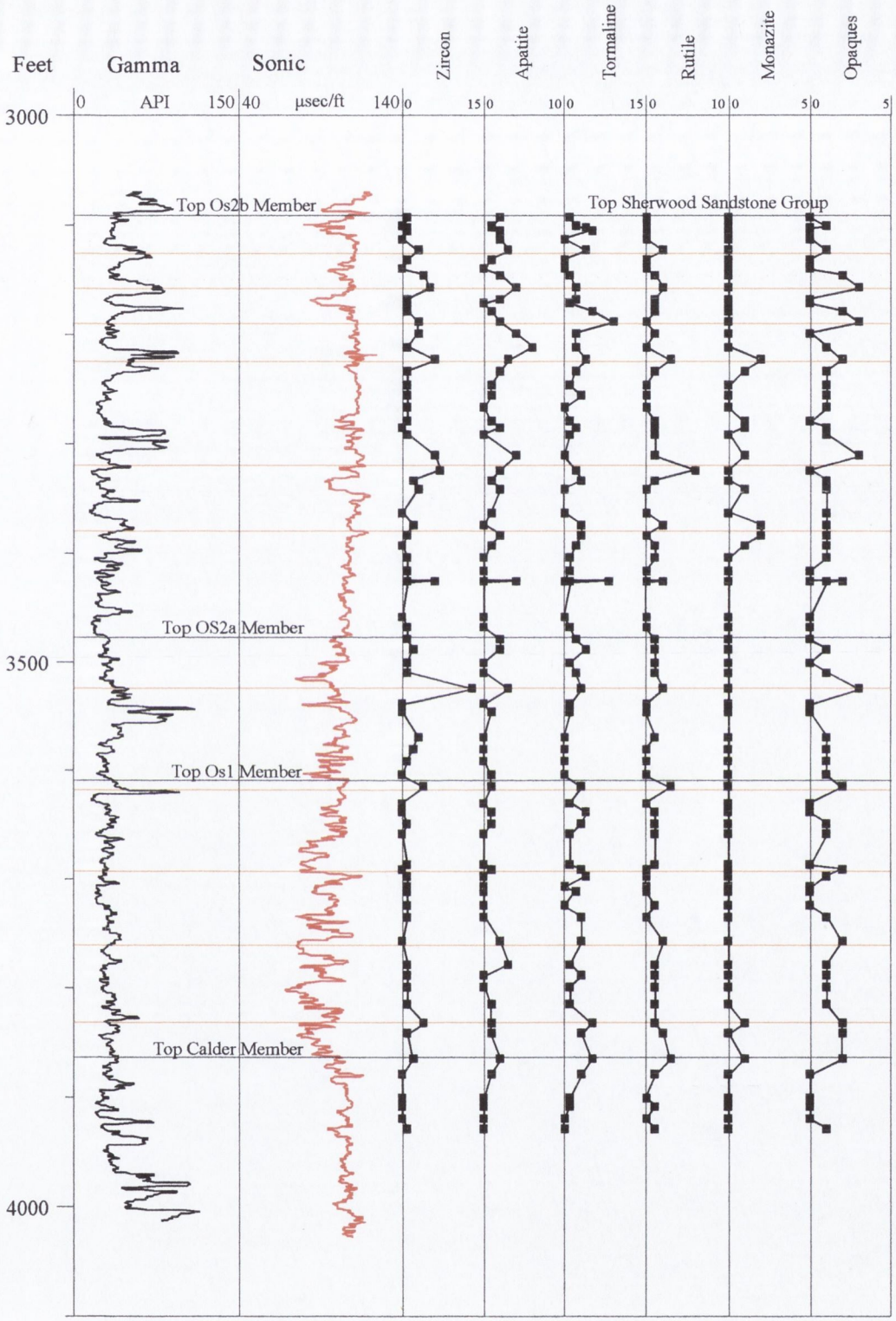


Figure 4.20 Heavy mineral counts for samples from well 110/2-6 plotted through the Ormskirk Sandstone Formation. Current stratigraphy shown in black and suggested influxes in red.

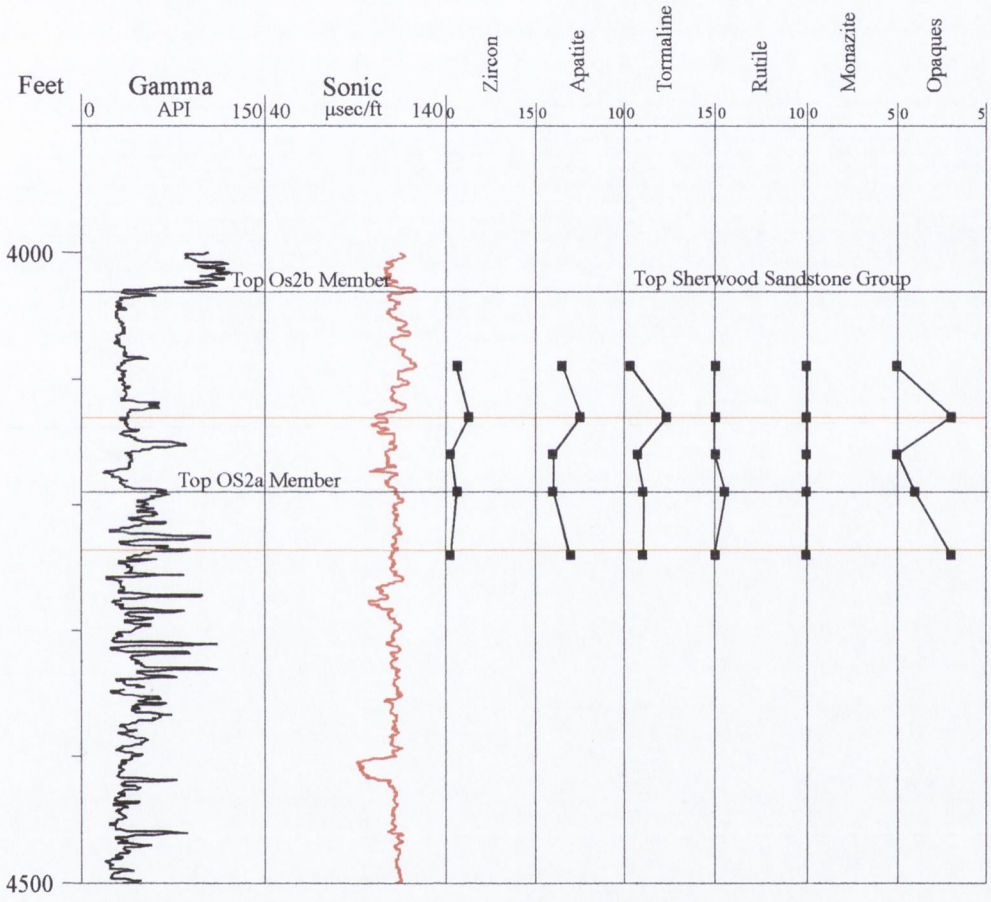


Figure 4.21 Heavy mineral counts for samples from well 110/8a-5 plotted through the upper part of the Ormskirk Sandstone Formation. Current stratigraphy shown in black and suggested influxes in red.

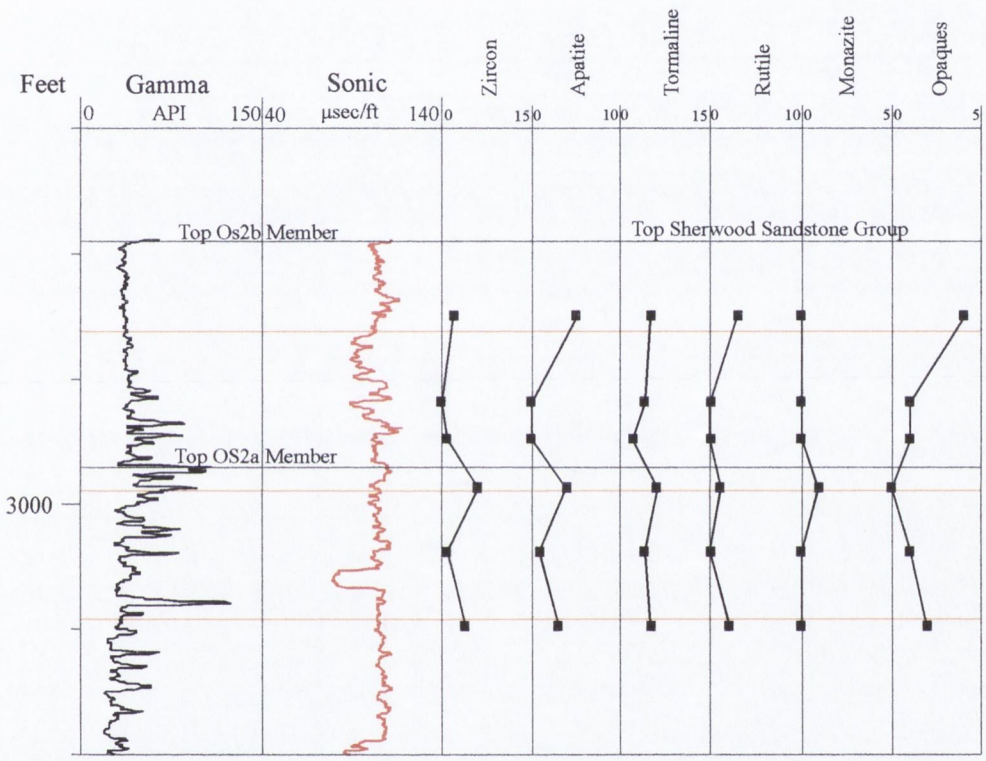


Figure 4.22 Heavy mineral counts for samples from well 110/13-5 plotted through the upper part of the Ormskirk Sandstone Formation. Current stratigraphy shown in black and suggested influxes in red.

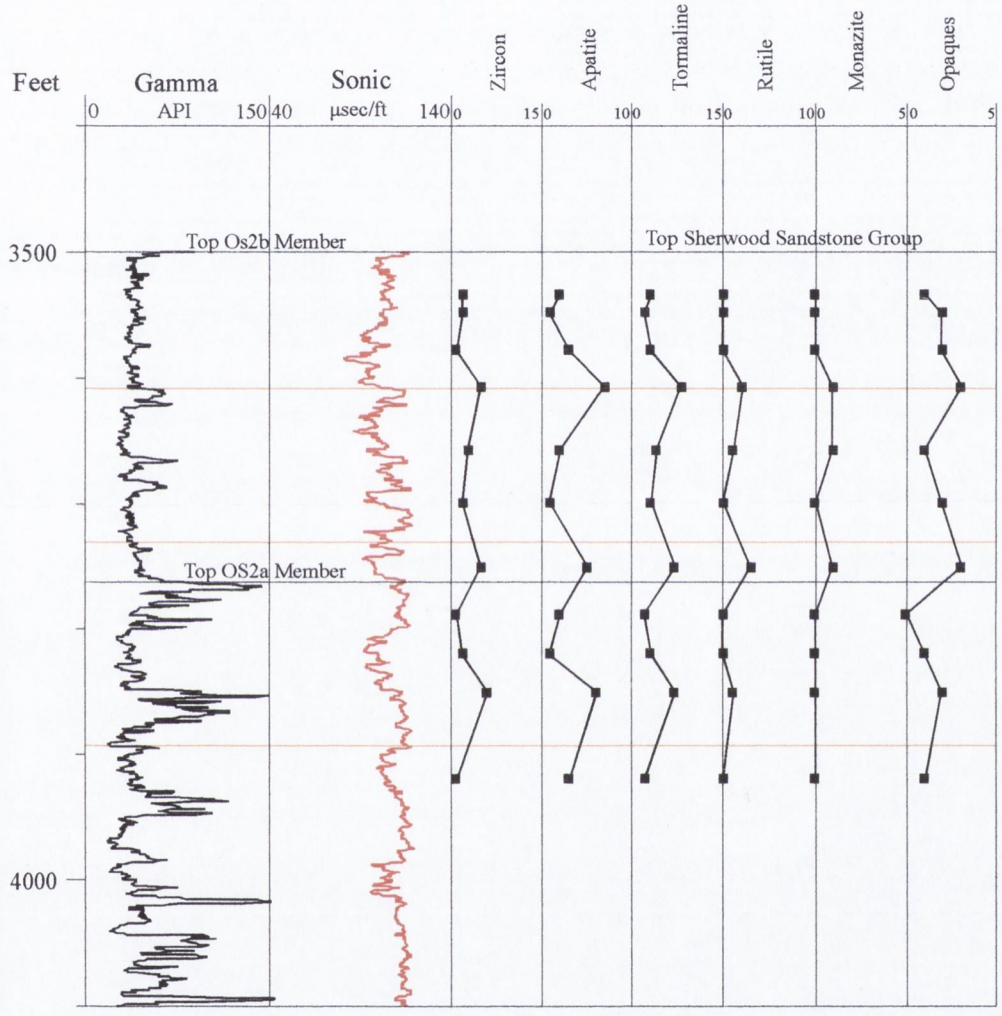


Figure 4.23 Heavy mineral counts for samples from well 110/14-3 plotted through the upper part of the Ormskirk Sandstone Formation. Current stratigraphy shown in black and suggested influxes in red.

5. SHERWOOD SANDSTONE GEOCHEMISTRY

5.1 INTRODUCTION

A total of 177 samples have been analysed for whole rock geochemistry from the four offshore East Irish Sea Basin wells that have been sedimentologically logged (wells 110/2-6, 110/8a-5, 110/13-5 and 110/14-3). The sampling has been concentrated in the upper part of the Ormskirk Sandstone Formation where facies heterogeneity, both vertically and laterally, is at its greatest but extending sufficiently far down into the succession to penetrate through the uppermost of the major stacked fluvial channel sandbodies. The majority of the samples were taken from core but a total of 55 were taken from washed and dried cuttings so as to obtain data from the reservoir interval above the core and below the cores in wells 110/8a-5 and 110/14-3. All of these samples have been subjected by Dr Nick Walsh of Royal Holloway College, London University, to ICP-AES (Inductively Coupled Plasma - Atomic Emission Spectrometry) and ICP-MS (Inductively Coupled Plasma – Mass Spectrometry) to obtain elemental analyses following the techniques outlined below.

The samples were analysed using Perkin Elmer Optima 3300 ICP-AES and Elan 5000 ICP-MS instruments with analytical procedures following those established by Thompson and Walsh (1989). The samples were first crushed in a Swing Mill grinder, reducing the sample to a fine powder. The samples were then weighed (0.5g) into teflon crucibles and evaporated to dryness with hydrofluoric and perchloric acids. This was then dissolved in 10% HCl acid and diluted to 50ml with distilled water. The overall dilution of the sample to 1:100 is optimum for ICP-AES analysis. The dissolved samples were then analysed with the ICP atomic emission spectrometer for Al, Fe, Mg, Ca, Na, K, Ti, P and Mn as weight percent oxides and Ba, Co, Cr, Cu, Li, Ni, Sc, Sr, V, Zn as parts per million. In addition, the powdered samples were fused (0.5g) with lithium metaborate, dissolved in 5% nitric acid and diluted to 250ml. This solution was then used for the determination of Si and Zr by ICP-AES. The solution was also used (after a 10 fold dilution) for the determination of Y, La, Ce, Nd, Sm, Eu, Dy and Yb using ICP-MS. The precision (reproducibility) is comparable to other analytical methods (±2% for the major constituents), accuracy being assessed by analysing a number of international standard reference materials covering the range of compositions found and was not significantly worse than the measured reproducibility. Detection limits can be taken as approximately 5

parts per million for trace elements measured by ICP-AES (although theoretical instrument detection limits are significantly lower). Detection limits for the trace elements measured by ICP-MS are better than 1 part per million for most elements. Standards were run every tenth sample so as to correct the machine for instrument drift. The resultant data was supplied directly as a spreadsheet for examination and interpretation. This is presented in Appendix IV.

5.2 DATA MANIPULATION

Following procedures established for the interpretation of ICP data obtained from clastic sedimentary successions (e.g. Pearce and Jarvis 1992; Racey *et al.* 1995; Pearce and Jarvis 1995) the raw data was first assessed for any inter-dependence between elemental groups and for diagenetic overprints that would adversely effect the results. Common problems include significant proportions of carbonate cement that significantly influence CaO, MgO and sometimes Fe_2O values, gypsum/anhydrite cement that influences CaO values and clay content that can influence Al_2O_3, K_2O, Na_2O and Fe_2O values as well as a number of the trace elements. A comparison of the chemical data with that derived from petrographic modal analysis can be used to determine the extent to which carbonate and sulphate cements have affected chemical abundances, while crossplots of SiO_2 and K_2O against Al_2O_3 are routinely used to assess the influence of clay content.

In the present instance the effect of carbonate and sulphate cements is considerable. However, although carbonate cements, particularly ferroan dolomite, are present in significant and variable quantities throughout the Ormskirk Sandstone Formation and sulphates, notably anhydrite, is locally abundant in well 110/8a-5, the sampling method has largely avoided severely contaminated zones. In addition, CaO, MgO and Fe_2O are not present in significant quantities in any of the more important detrital grains in the succession analysed and, hence, these oxides have not been used in the stratigraphic determinations. It has, however, been found that the affect of clays is also significant and that their presence in variable amounts influences stratigraphically important elements such that the raw data require recalculation of both the oxide and trace element abundances.

In the first instance, a crossplot of SiO_2 against Al_2O_3 (Figure 5.1) reveals a strong negative trend, suggesting that it is influenced by the sand:clay ratio in that, as silica

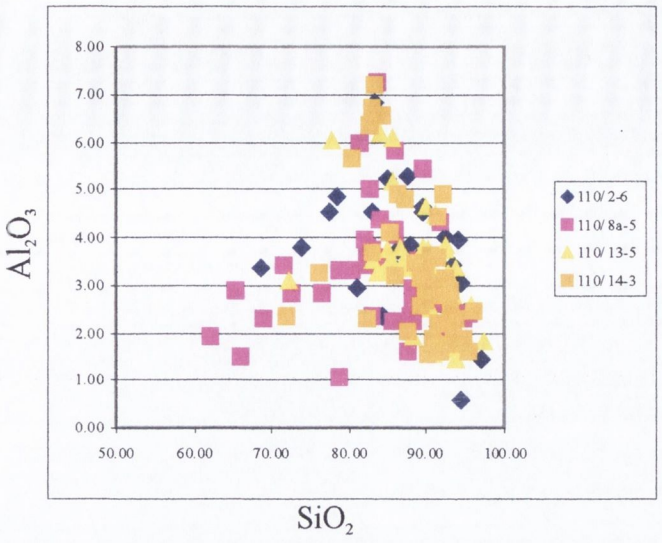


Figure 5.1
Raw ICP-AES data showing a strong negative trend of Al_2O_3 v SiO_2 indicative of a lithological control on oxide abundances. Those data plotting below the main axis are predominantly partially carbonat and sulphate cemented samples

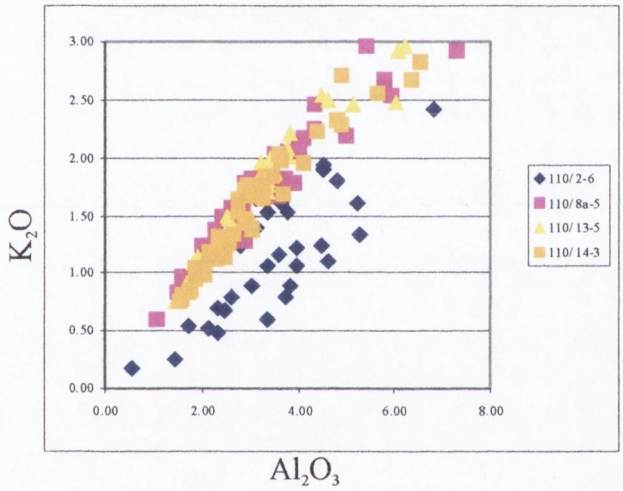


Figure 5.2
Positive correlation of K_2O and SiO_2 in raw ICP-AES data supports inference in Figure 5.1 and further reveals depletion of K_2O in well 110/2-6 due to illite transformations

decreases, the clay content as measured by Al_2O_3 increases. The data points plotting off this trend, specifically those with low SiO_2 and Al_2O_3 values, are the more carbonate and sulphate rich samples. A crossplot of K_2O against Al_2O_3 (Figure 5.2) reveals a similarly strong positive trend (R^2=62.5%) although it is noticeable that the data from well 110/2-6 has consistently lower values of K_2O that the other wells (without well 110/2-6 the R^2=>90%). The reason for this becomes apparent with reference to comments on the authigenic mineralogy of the rocks in Section 4.3 where it is clear that the samples from well 110/2-6 contain rather more illite, much of it derived by the breakdown and alteration of detrital clays in particular but also K-feldspar, than the other wells. Macchi (1987) notes that the transformation of smectitic clays and K-feldspar to illite requires the excess liberation of both Si^{4+} and K^+ in order to release sufficient aluminium for illite

precipitation, thereby implying that the process has to lose silica and potassium into the porewaters.

The raw whole rock geochemical data is therefore biased towards the sand:clay ratio of the rocks, a not uncommon problem, and requires normalization before being used in any comparison with the detrital mineral assemblage. In practice this problem is usually corrected by normalization against Al_2O_3, this being taken as a proxy for the clay percentage in the samples (e.g. Pearce and Jarvis 1992; 1995; Pearce *et al.* 1999). Where this process is carried out it is advisable to check that the inter-dependence of the data sets has been removed. Clearly this cannot be checked by plotting other oxides against Al_2O_3 following normalization but, given that K_2O correlates closely with Al_2O_3 in the raw data, as it does in the present case, this can be plotted against SiO_2 (Figure 5.3) and used to validate the normalized data. This manipulation of the data has proved somewhat unsatisfactory in the present case, mainly it is presumed in response to the highly variable K-feldspar content of the sandstones. A crossplot of K_2O against SiO_2 (Figure 5.4) normalized by this method reveals a mathematical rotation of the data that has not completely removed the inter-dependence of the oxide percentages. Clearly the Al_2O_3 content of the feldspars forms a significant component of the total Al_2O_3 in the sandstones.

An alternative to this generally accepted practice is provided by the wireline log data for the wells in that the API gamma log can be also be taken as a proxy for the clay content. Normalization of the chemical data against this value has generated the dataset from which Figure 5.5 is plotted and in which it can now be seen that the inter-dependence of the K_2O and SiO_2 values has been removed entirely. A plot of Al_2O_3 against SiO_2 (Figure 5.6), which can be utilised following normalization against API gamma, confirms this assumption. The possibility of using Zn as a proxy for clay content, as advocated by Svendsen and Hartley (2001), was dismissed on the grounds that, unlike the Otter Sandstone in east Devon on which these authors based their findings, the Sherwood Sandstone in the East Irish Sea Basin includes variable quantities of ferromagnesian heavy minerals that are likely to contain Zn in significant and un-quantifiable proportions that could therefore invalidate the results.

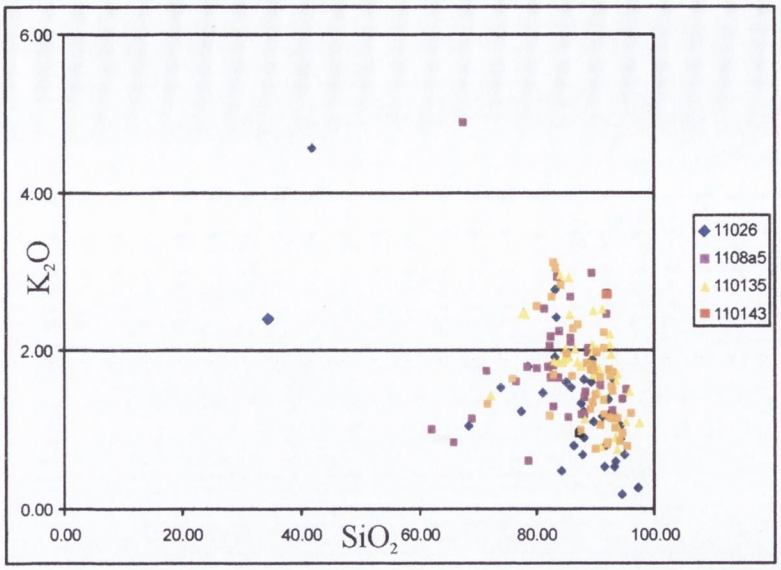


Figure 5.3
Raw ICP-AES data for K_2O and SiO_2 showing a similar negative correlation to that for Al_2O_3 and SiO_2 in Figure 5.1

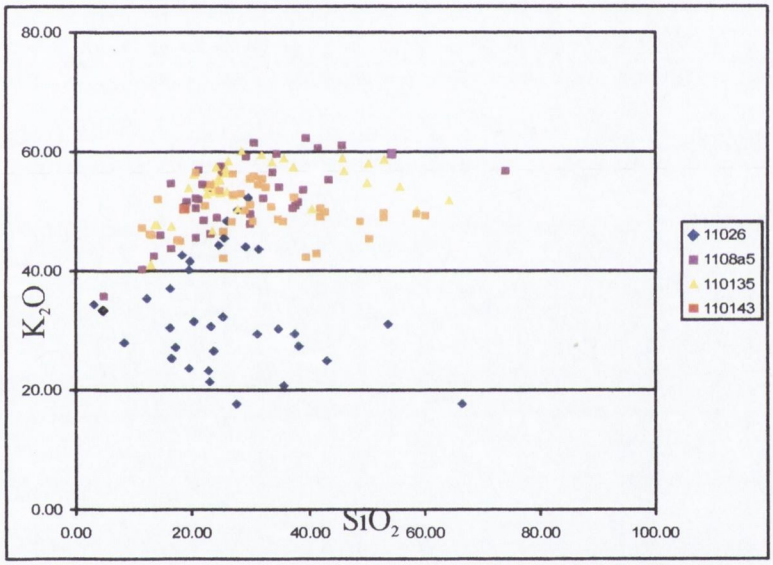


Figure 5.4
ICP-AES data normalised against for Al_2O_3 but revealing a slight positive correlation between K_2O and SiO_2 suggesting that there is still a residual inter-dependence in the data

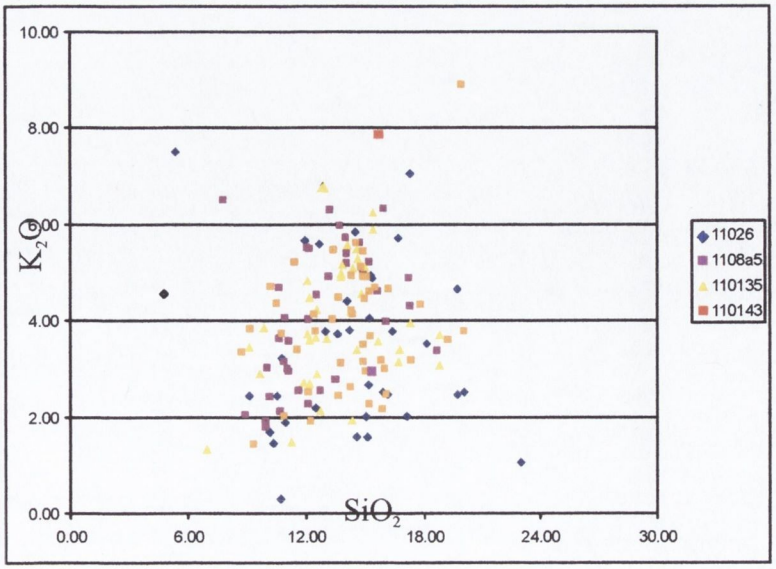


Figure 5.5
ICP-AES data normalised against the API gamma from wireline data and revealing no discernible inter-dependence between K_2O and SiO_2

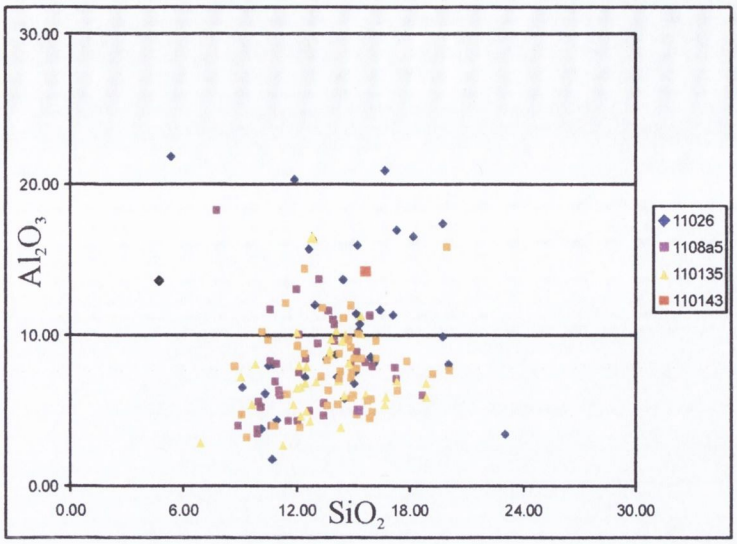


Figure 5.6
Normalised ICP-AES data for Al_2O_3 and SiO_2 showing a near random scatter of data points. Compare to Figure 5.1

5.3 DOWNWELL PLOTS

Downwell plots showing the full normalised data set for each well are presented in Appendix IV but, for ease of presentation and discussion, selected oxide and trace element plots are reproduced in Figures 5.7-5.10. These include the plots found to have the greatest stratigraphic significance, Al_2O_3, K_2O, Na_2O, TiO_2, Y, Zr, La and Ce, and relevance to the mineralogical data as discussed below. Picks deemed to be of particular importance are highlighted on the figures where there are upward changes between two data points in the oxides relevant to feldspar abundance or particular peaks in the trace elements that can be related to specific heavy minerals.

It is apparent that, following normalization against API gamma, the Al_2O_3 and K_2O plots tend to track each other in all four wells, suggesting an inter-relationship that, as it can be now only minimally related to the sand/clay ratio in the normalised data, is best interpreted as representing mainly the K-feldspar content of the sandstones (see further discussion in Section 6 below). In particular, there is a general upward increase and then decrease in the Al_2O_3 and K_2O tracks in the lower part of the sampled intervals of all four wells and a significant upward increase in both within the upper parts of the intervals. These latter occur at approximately 3195ft in well 110/2-6, 4210ft in well 110/8a-5, 2965ft in well 110/13-5 and 3705ft in well 110/14-3. It is equally noticeable that, although not identical, there are corresponding changes in the abundance of Na_2O with a significant upward increase in this oxide at the same depths as those noted for K_2O. Comparison of the

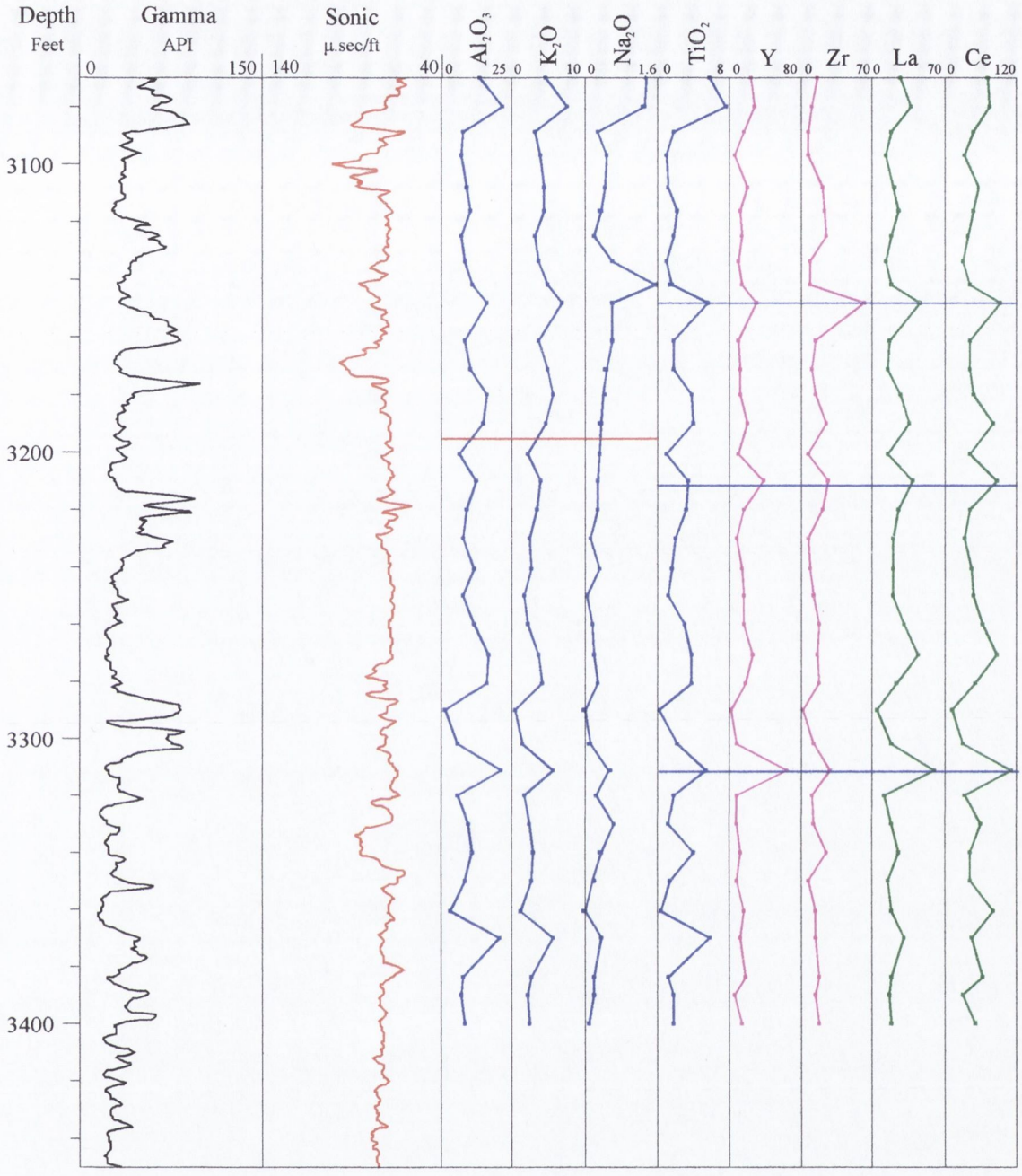


Figure 5.7 Well 110/2-6, selected normalized oxide and trace element data

Key		
		Inferred upward increase in feldspars
		Inferred peaks in heavy mineral content

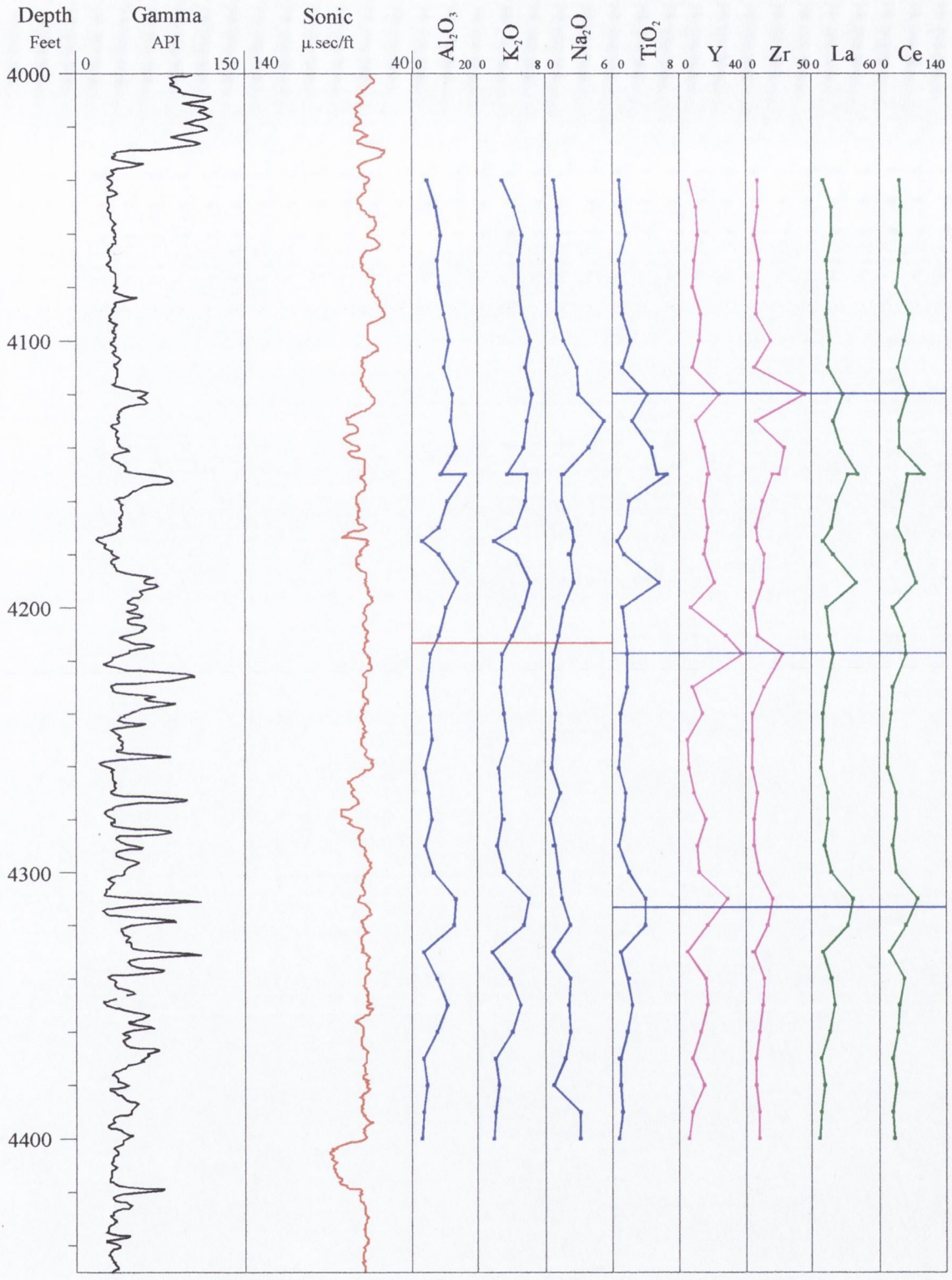


Figure 5.8 Well 110/8a-5, selected normalized oxide and trace element data.

Key	
	Inferred upward increase in feldspars
	Inferred peaks in heavy mineral content

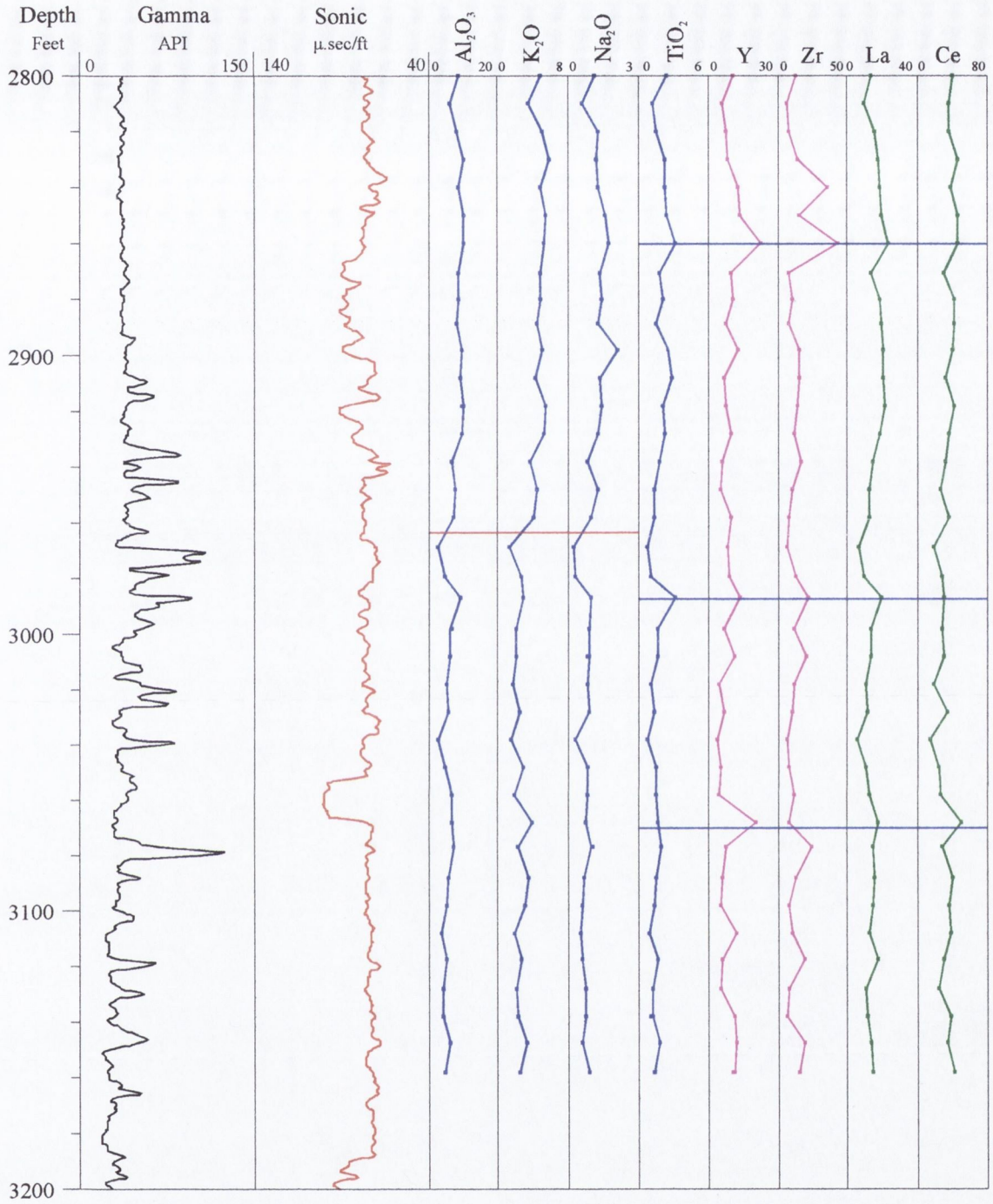


Figure 5.9 Well 110/13-5, selected normalized oxide and trace element data)

Key	
	Inferred upward increase in feldspars
	Inferred peaks in heavy mineral content

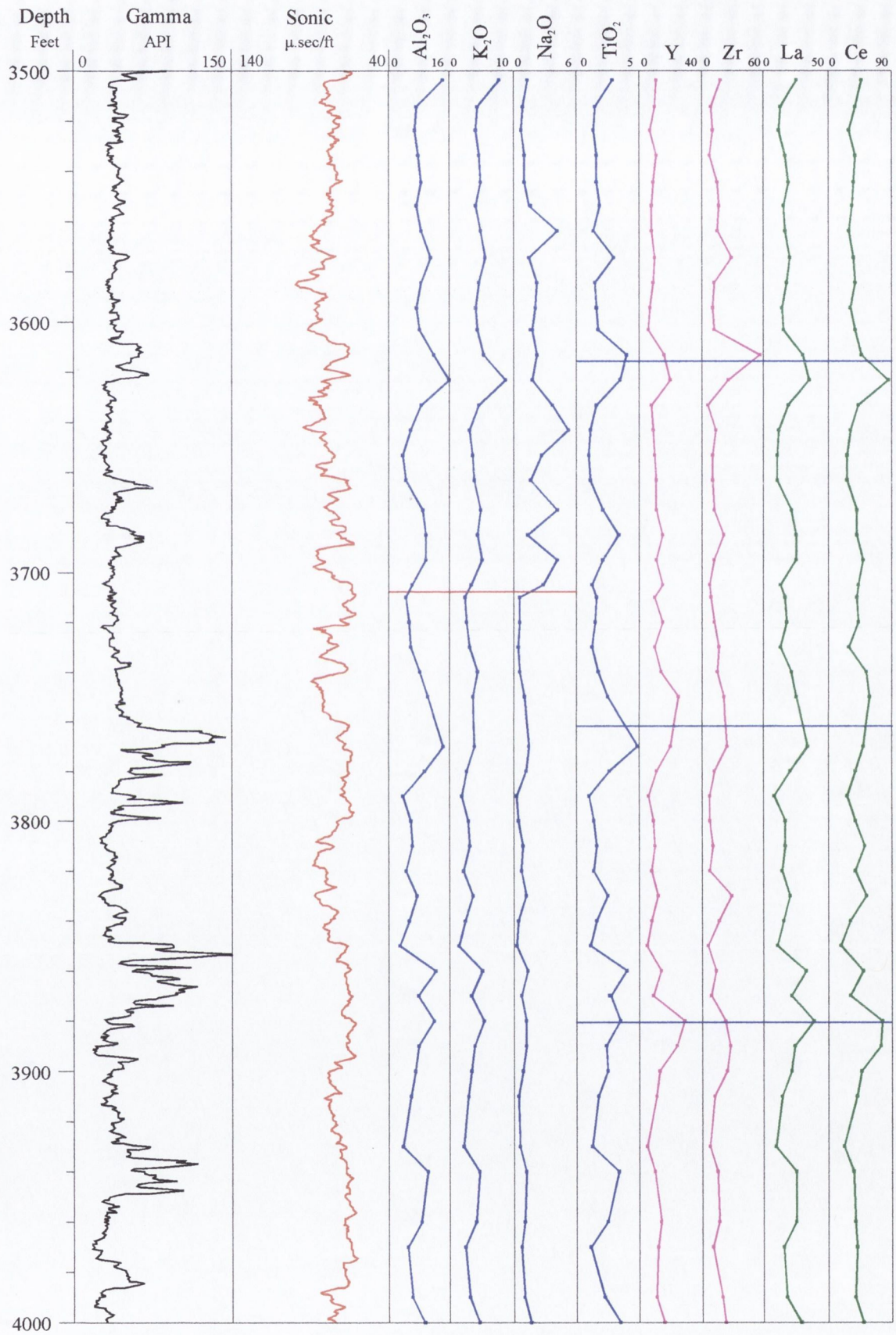


Figure 5.10 Well 110/14-3, selected normalized oxide and trace element data.

Key	
	Inferred upward increase in feldspars
	Inferred peaks in heavy mineral content

horizontal scales for the Na_2O data suggests that this oxide is somewhat more abundant in well 110/14-3 than in the other wells, potentially implying a geographical variation in addition to the stratigraphic variations described.

Given the detrital mineralogy of the Sherwood Sandstone Group sandstones, as previously discussed in Section 4.2, the trace element zirconium only occurs in any measurable quantities within the heavy mineral zircon. There is a possibility that zircon crystals occur as inclusions within biotite grains although none have been noted during thin section analysis and biotite itself is of trace occurrence such that this can be considered negligible. Similarly, the trace element yttrium (Y) occurs mainly as an ionic substitute for calcium into the heavy mineral apatite, while lanthanum (La) commonly substitutes for cerium within monazite (Deer *et al.* 1992). The downwell traces for each of these trace elements, together with TiO_2 which occurs principally as the primary constituent of rutile, anatase and ilmenite, reveal distinctive peaks at specific and corresponding stratigraphic horizons. There are, most notably, increases in the abundance of all these elements at approximately 3150ft, 3210ft and 3310ft in well 110/2-6, at 4120ft, 4210ft and 4310ft in well 110/8a-5, at 2860ft, 2990ft and 3070ft in well 110/13-5 and at 3610ft, 3750-3770ft and 3880ft in well 110/14-3. It is tempting, but not conclusive from the chemical data alone, to suggest that these peaks in the elemental abundances represent an increased occurrence of the associated heavy minerals within the sandstones. There is clearly the possibility that, even where a positive correlation can be established between heavy mineral assemblages and trace element abundances, this may represent hydraulic sorting within either fluvial channels or aeolian dunes and sandsheets. Comparison of the stratigraphic position of the elemental peaks with those determined from the count of heavy minerals (Section 4.4 and as shown on Figures 5.7-5.10) reveals a close correspondence and, as discussed in Section 4.4, covers the majority of the depositional facies present within the Sherwood Sandstone Group. It therefore appears unlikely that hydraulic sorting is responsible for the increased heavy mineral abundances and more likely that they record episodes during which sandstones relatively enriched in these mineral species were being input to, and deposited within, this area of the East Irish Sea Basin.

5.4 STRATIGRAPHIC DISTRIBUTION

The database derived from ICP-AES and ICP-MS analyses covers the upper parts of the Ormskirk Sandstone Formation from close to the contact with the overlying Mercia Mudstone Group down and into the prominent stacked and amalgamated fluvial channel sandstones that are assigned to the OS2a Member within the current lithostratigraphy (Figure 1.2). The most notable feature of the interpreted chemical dataset, and potentially most important stratigraphically, is the subdivision of this interval into an upper unit that is clearly relatively enriched in K_2O and Na_2O, which implies enrichment in K-feldspar and plagioclase, and a lower unit in which K_2O and Na_2O are sparse or even locally absent. From discussions above it is apparent that the difference in the abundance of feldspars cannot be ascribed to diagenetic modifications to the sandstone composition and must therefore reflect variations in the detrital assemblage that occurred during deposition.

Similar arguments can be applied to the increases in the heavy mineral content of the sandstones in that the correspondence of the trace element peaks representing different mineral species and their occurrence at discrete horizons tends to suggest repeated influxes of sandstones enriched in these minerals, especially apatite, zircon and monazite.

While it is possible that the inferred upward increase in the feldspar content of the sandstones occurred diachronously across the East Irish Sea Basin, the extent of fluvial reworking and the common interchange of sediment between channels and sandflats that is attested to within the sedimentological data would suggest that any diachroneity is minimal. It seems likely, therefore, that the transition to a more feldspar rich assemblage reflects a significant change in either the provenance of the sandstones or in their residence time during transportation. Morton (1984) has noted that feldspar grains, among a selection of heavy minerals including apatite and monazite, are subject to dissolution under acidic groundwater conditions and prolonged sediment storage within the hinterland could therefore result in mineralogical changes to the detrital assemblage.

Notwithstanding the cause of the chemical variations in the Sherwood Sandstone, it is clear from the plots that each well displays a similar character in the K_2O and Na_2O traces which therefore provides a potential basis for a chemically defined correlation. Additionally, the character of the implied heavy mineral peaks are also similar in that the uppermost peak

appears in all four wells to exhibit a particularly high concentration of Zr, while the lowermost is generally more enriched in Y and La. The middle peak, lying variably some 20-45ft below the noticeable change in the K_2O and Na_2O traces, is the least well defined in all wells apart from 110/8a-5 where it exhibits high concentrations of Y and Zr. The relative stratigraphic position of all three trace element peaks, and their order relative to the upward increase in K_2O and Na_2O, is the same in all four wells, supporting the concept that these changes in oxide and elemental abundances may have correlative and stratigraphic significance.

6. ORMSKIRK AND HELSBY SANDSTONE FORMATIONS

6.1 INTRODUCTION

A number of comments have been made previously with respect to the problems associated with existing well correlations in the East Irish Sea Basin (see Sections 2.3 and 2.4). These combined with the comments above detailing the clear inconsistencies apparent in the currently accepted lithostratigraphy imply the need for a revised model based upon a more robust stratigraphic framework.

As currently defined the Ormskirk and Helsby Sandstone Formations are taken to represent distinct and identifiable stratigraphic units forming the uppermost part of the Sherwood Sandstone Group in the East Irish Sea and Cheshire Basins respectively (Jackson *et al.* 1995; Warrington *et al.* 1999). While the tops of the two formations are relatively easy to determine in the East Irish Sea Basin and the northern parts of the Cheshire Basin, being defined by the contact with the claystones, halites and dolomites of the overlying Mercia Mudstone Group, their internal subdivisions and bases are considerably more equivocal and inconsistent both between basins and between authors.

6.2 SUBDIVISIONS

The informal subdivision of the Helsby Sandstone Formation (then Keuper Sandstone Formation) by Thompson (1970a) into Frodsham, Delamere and Thurstaston Members provided a stratigraphic framework that has been reproduced and re-interpreted by nearly all subsequent authors considering the Sherwood Sandstone stratigraphy in both the East Irish Sea and Cheshire Basins. Working primarily on outcrop and shallow borehole data in the area from the Wirral across the northwest and northern parts of the Cheshire Basin, Thompson (1970a) defined the members on the basis of lithofacies ascribed to a range of sedimentary environments including aeolian dunes, low sinuosity fluvial channels including abandonment deposits and floodplains or lagoons and tidal flats. The relative abundance, or dominance, of a lithofacies within each of the members was used as the defining criterion with an uppermost unit of soft sandstones (aeolian) defining the Frodsham Member, red pebbly sandstones (fluvial) defining the Delamere Member and a further lower succession of soft sandstones defining the lowermost, Thurstaston Member. Thompson (1970a) did, however, recognise lateral changes that disrupted this layer-cake

arrangement and also proposed a Nether Alderley Member comprising pebbly sandstones into which the Frodsham Member locally passed laterally and an Alderley Conglomerate Member locally forming the base of the Formation and into which the Thurstaston Member also passed laterally. In the absence of the pebbly Alderley Conglomerate Member Thompson (1970a) does not attempt to define in any detail the base of the Helsby Sandstone Formation or to distinguish it from the underlying Wilmslow Sandstone Formation (then Bunter Upper Mottled Sandstone) which apparently also comprises the soft sandstone lithofacies.

Drawing sedimentological conclusions from the stratigraphical subdivisions of Thompson (1970a) it is apparent that the Frodsham Member is dominantly aeolian with some fluvial intercalations, that the Delamere Member is dominantly fluvial and the Thurstaston Member is partly aeolian, partly fluvial and can only be used to define the base of the formation where pebbly fluvial channel sandstones happen to be present. This effectively becomes a circular argument as the presence of such sandstones, regardless of their true stratigraphic position, become the defining criterion leading to implied variations in the supposed thickness of both the member and the formation. This problem has been glossed over by most subsequent authors and, in part, circumnavigated by Warrington *et al.* (1999) who rightly consider the Thompson members to be 'facies associations whose stratigraphical order may vary laterally' and then go on to place the base of the Helsby Sandstone at the 'unconformable' base of the mainly fluvial Delamere Member.

In the offshore areas, especially the southern parts of the East Irish Sea Basin, the tripartite subdivision of Thompson (1970a) has been successfully applied to oil and gas fields now operated by BHP Billiton Petroleum Limited. The main reservoir intervals in the Lennox Field (Haig *et al.* 1997) and the Douglas Field (Yaliz 1997) are divided into Frodsham, Delamere and Thurstaston Members of the Ormskirk Sandstone Formation on the basis of wireline log character (see Section 2.3) coupled with sedimentary facies determined from cored intervals. As with the onshore, the Frodsham Member is largely aeolian but it is noted that fluvial channel sequences are present within it (Yaliz 1997), the Delamere Member is largely fluvial and the Thurstaston Member comprises a mixed facies association of aeolian and fluvially deposited sediments. The base of the Thurstaston Member, and hence the Ormskirk Sandstone Formation is, however, defined by an abrupt

downward change into further fluvial channel sandstones that is readily picked from its wireline log signature (see Section 2.3). This distinction therefore implies that the base of the Ormskirk Sandstone is defined by a downward transition from aeolian to fluvial sandstones whereas the supposedly equivalent base of the Helsby Sandstone is defined, where it is possible to achieve this, by a downward transition from fluvial to aeolian sandstones.

Northwards in the East Irish Sea Basin in and around the South Morecambe Field the definition of three members becomes more problematical (see comments in Section 2.3) with, for example, somewhat arbitrary two and three fold subdivisions being applied to wells 110/2-6 and 110/2b-9 (Appendix I) whereas, if the strict wireline/sedimentological criteria are adhered to, it is possible to subdivide the Ormskirk Sandstone in these wells into anything between six and fourteen identifiable units. As discussed in Section 2.2 there are good correlations between sedimentary facies and wireline log characteristics such that facies interpretations can be extended beyond the limits of core control. These potentially numerous subdivisions of the Ormskirk Sandstone in the region of the Morecambe Field therefore imply that the dominant facies associations which define the members to the south are breaking down northwards with the development of a considerably more complex vertical interdigitation of fluvial channel, sandflat and aeolian sequences.

Further north again, from the Millom Field (wells 113/26-2 and 113/27-3) to well 112/25a-1 in the extreme northwest of the East Irish Sea Basin and into west Cumbria the subdivision of the Ormskirk Sandstone apparently reverts to a more simple arrangement of facies associations. The Millom Field wells appear to lend themselves to a bipartite subdivision, or potentially four-fold in the case of well 113/26-1, while well 112/25a-1 can just be subdivided into three but, on the basis of a limited wireline suite, may well be dominated by aeolian/sandflat sequences with very sparse fluvial intercalations. Similarly, the Ormskirk Sandstone in Cumbria as described by Barnes *et al.* (1994), from limited outcrop data but extensive borehole coring associated with exploratory drilling at Sellafield, is also dominated by aeolian sandstones with little or no fluvial channel facies being recorded. In accordance with criteria cited above for wells further south the base of the Ormskirk Sandstone in west Cumbria is taken at a sharp downwards break to fluvial

channel sandstones that are used to define the upper part of the underlying Calder Member of the St Bees Sandstone Formation (Barnes *et al.* 1994).

6.3 REVISED CORRELATIONS

The mineralogical and chemical data discussed in Sections 4 and 5 respectively, especially that derived from the four wells examined in detail, provide the basis for new well correlations that reflect changes through time in the mineralogy of the sandstones being deposited within both the East Irish Sea and Cheshire Basins. While it can be accepted that such changes are unlikely to be isochronous across an area as large as the East Irish Sea Basin, the possibility that variations in the mineralogy can be correlated at least provides an alternative stratigraphic framework that is potentially independent of sedimentary facies and arbitrary ill-defined surfaces such as the base or top of any particular fluvial channel complex. In addition, the extent of both fluvial and aeolian reworking apparent from the sedimentology suggests that mineralogical changes may have occurred, and been recorded, in relatively short episodes of time and may therefore be the nearest approximation to time lines (or time surfaces) that can be established within the Sherwood Sandstone Group (but note comments in Section 9.4 regarding the correlation of climatically mediated sandflat facies).

The selection of mineralogical and chemical data most likely to provide a robust stratigraphic framework is based upon those components of the detrital mineralogy that are complementary, as detailed in Figures 6.1–6.4 for wells 110/2-6, 110/8a-5, 110/13-5 and 110/14-3 respectively. There is clearly a close correspondence of K-feldspar and plagioclase feldspar abundances with the Al_2O_3 data and with K_2O and Na_2O data respectively as derived from ICP-AES analyses. This indicates significant changes in the overall feldspar content of the sandstones through time. In particular, the upward increase in feldspar noted in all four wells appears to occur within the upper parts of the stacked fluvial channel succession nominally ascribed to the OS2a Member within wells 110/2-6, 110/8a-5 and 110/13-5 but lies within an aeolian dominated succession ascribed to the OS2b Member within well 110/14-3. The further downward increase in feldspar recorded from the modal analysis data in well 110/2-6 through the lower parts of the Ormskirk Sandstone, while unsupported by chemical analyses, suggests that the feldspar content of

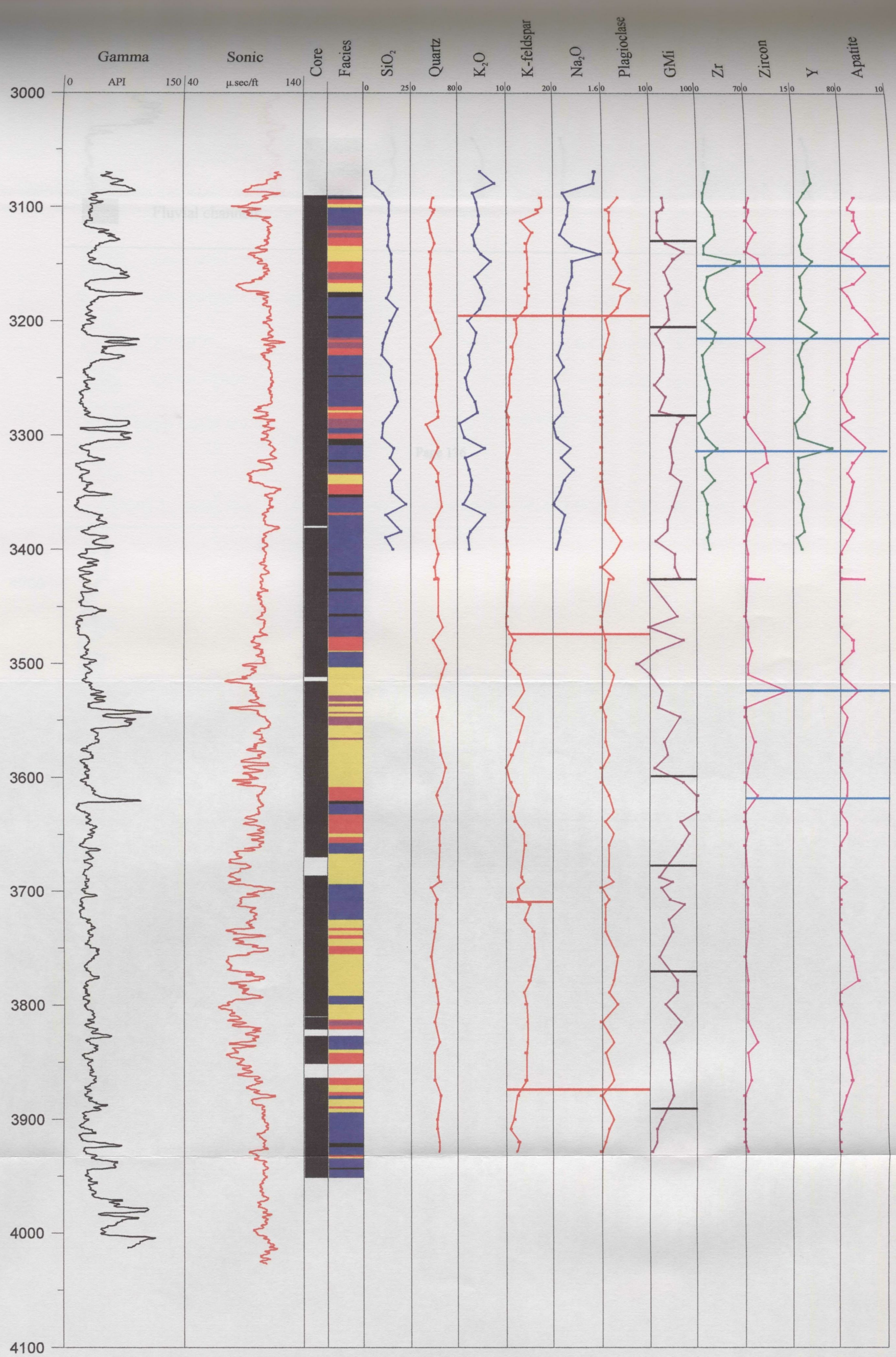


Figure 6.1 Well 110/2-6: Composite chemical and mineralogical data related to detrital sandstone composition (facies colour codes and surface definitions as Figure 6.2).

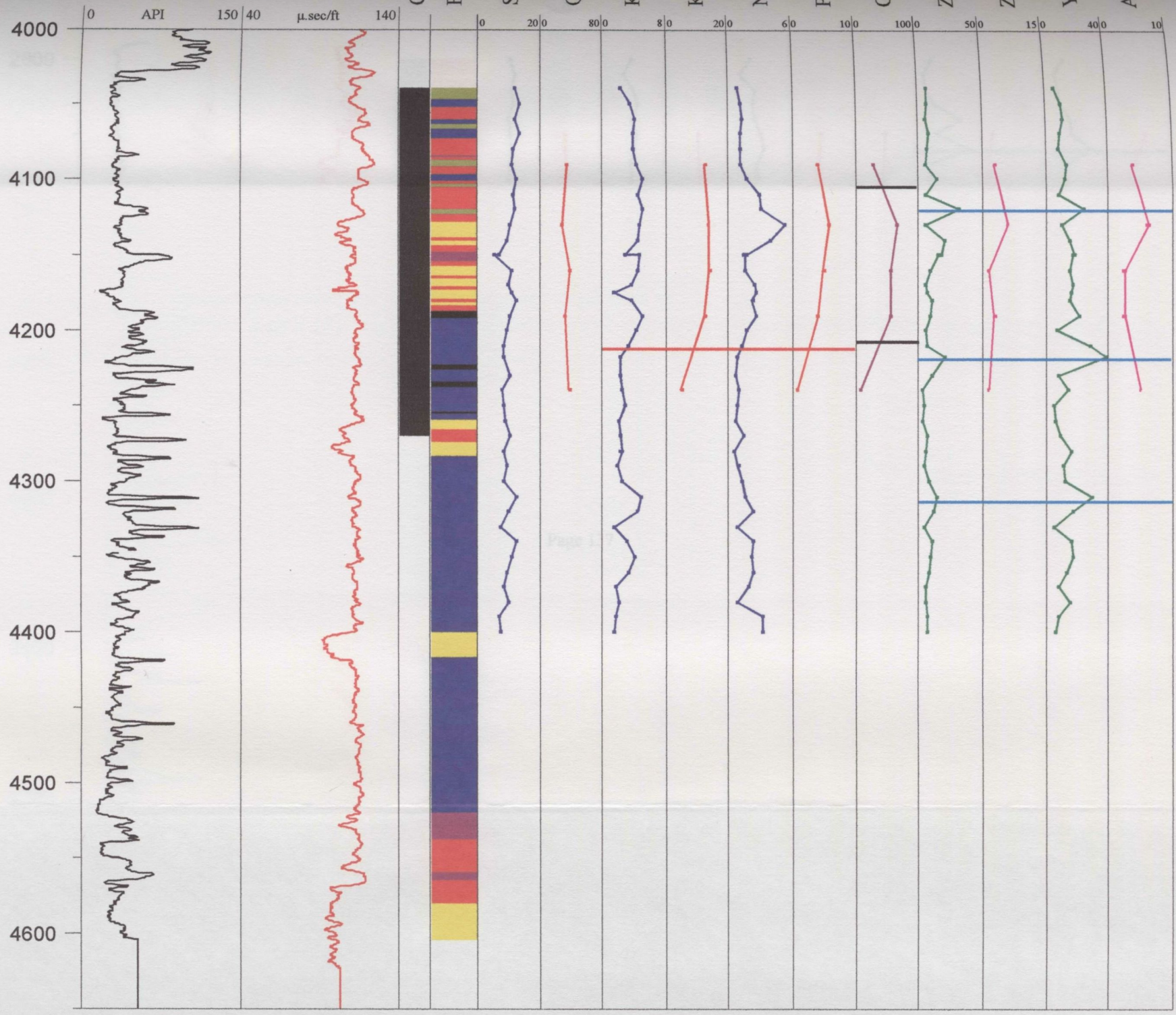


Figure 6.2 Well 110/8a-5: Composite chemical and mineralogical data related to detrital sandstone composition.

Key to facies colour codes

- Clastic sabkha
- Sandflats
- Aeolian dunes and sandsheets
- Playa lakes and margins
- Fluvial abandonment
- Fluvial channels

Significant surfaces

- Changes in feldspar content
- Heavy mineral peaks
- Changes in GMi

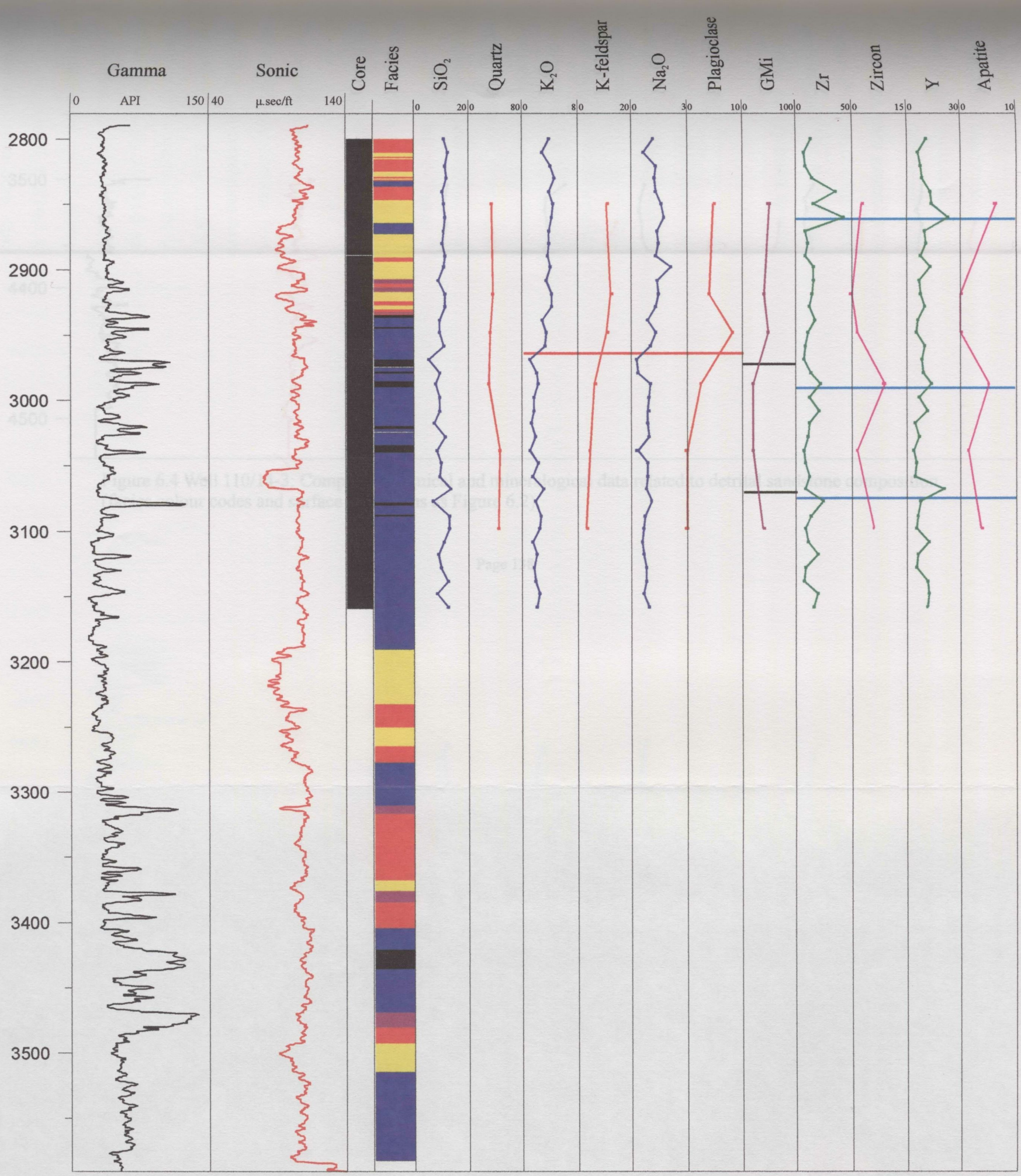


Figure 6.3 Well 110/13-5: Composite chemical and mineralogical data related to detrital sandstone composition (facies colour codes and surface definitions as Figure 6.2).

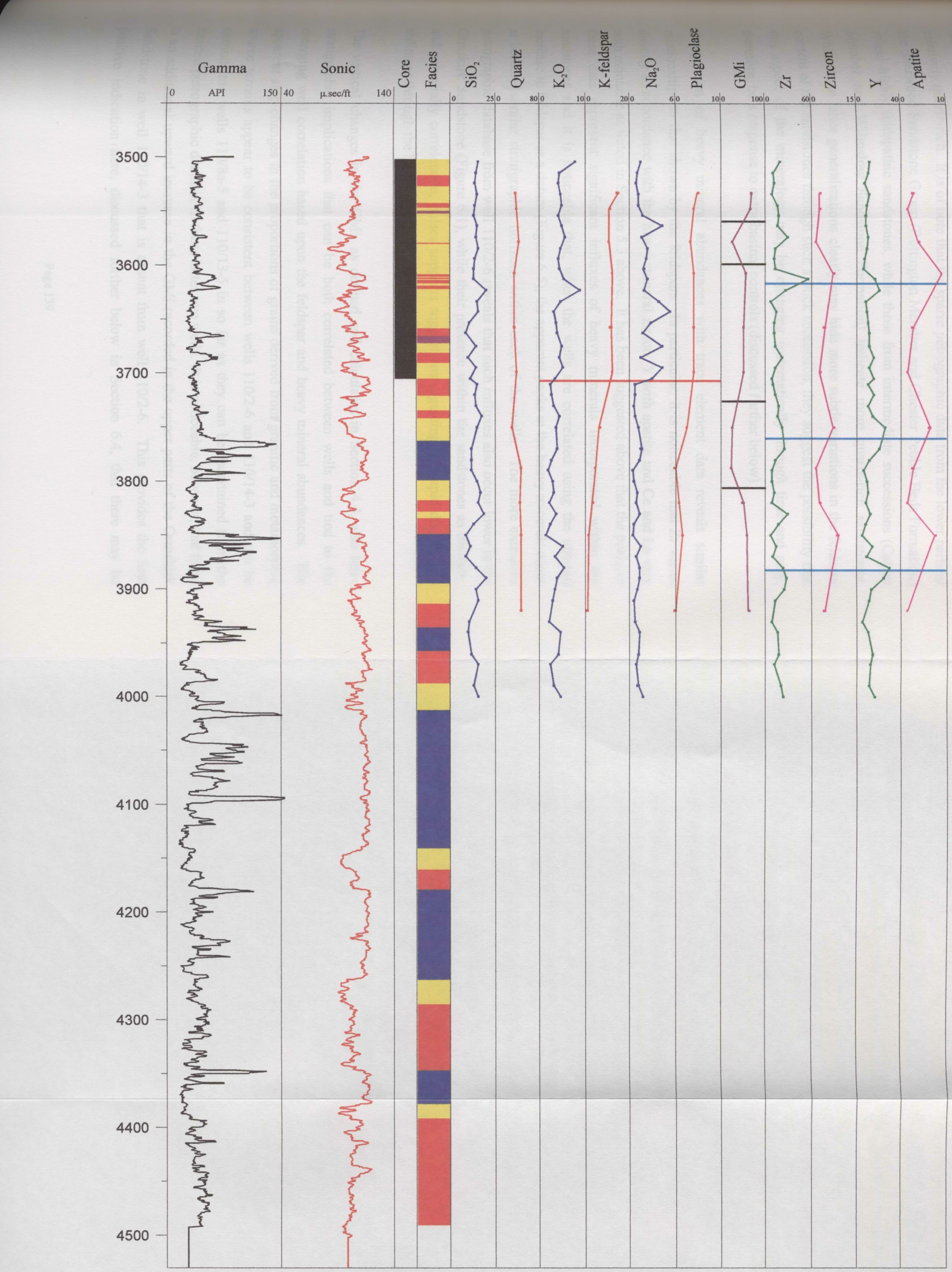


Figure 6.4 Well 110/14-3: Composite chemical and mineralogical data related to detrital sandstone composition (facies colour codes and surface definitions as Figure 6.2).

the sandstones may be varying between end-members that are relatively feldspar-rich and relatively quartz-rich. It is of note that the sparse petrographic data from the lower parts of the Sherwood Sandstone Group (Rottington Member and Chester Pebble Beds Formation) reveal highly feldspathic sandstones, while those from intermediate successions (Calder Member and Wilmslow Sandstone Formation) indicate more quartz-rich sandstones. While these latter generalizations clearly may hide more subtle variations in the feldspar content of the sandstones through such a thick succession, they suggest the possibility that this aspect of the mineralogy may be changing systematically through time and may, therefore, be a response to extra-basinal controls (discussed further below).

Comparison of heavy mineral abundances with trace element data reveals similar relationships to that shown by the feldspars. In particular, it is noticeable that Zr varies directly in accordance with the heavy mineral zircon, Y with apatite and Ce and La vary with monazite as noted in Section 5.3 above. It has been suggested above that the peaks in these data represent significant influxes of heavy minerals incorporated within the sandstones and it is noticeable that, when the wells are correlated using the upward increase in feldspar as a datum (Figure 6.5), the apparent peaks in the heavy minerals occur at broadly similar stratigraphic horizons within each of the wells. The more extensive petrographic database from well 110/2-6 reveals that such influxes also occur lower in the Ormskirk Sandstone (Figure 6.1), while their presence within the sandstones as discrete, and potentially correlatable, pulses supports suggestions regarding the rapid dispersal of sediment through the basin.

The vertical changes in the GMi, as defined and calculated in Section 4.4, also have stratigraphic implications that can be both correlated between wells and tied to the emerging well correlation based upon the feldspar and heavy mineral abundances. The apparent step changes in the proportions of grains derived from granitic and metamorphic source terrains appear to be consistent between wells 110/2-6 and 110/14-3 and can be carried into wells 110/8a-5 and 110/13-5 in so far as they can be ascertained from the limited petrographic database in these latter two wells. It is noticeable, however, that there is an additional upward increase in the GMi recorded in the upper parts of the Ormskirk Sandstone in well 110/14-3 that is absent from well 110/2-6. This provides the first positive indication here, discussed further below in Section 6.4, that there may be

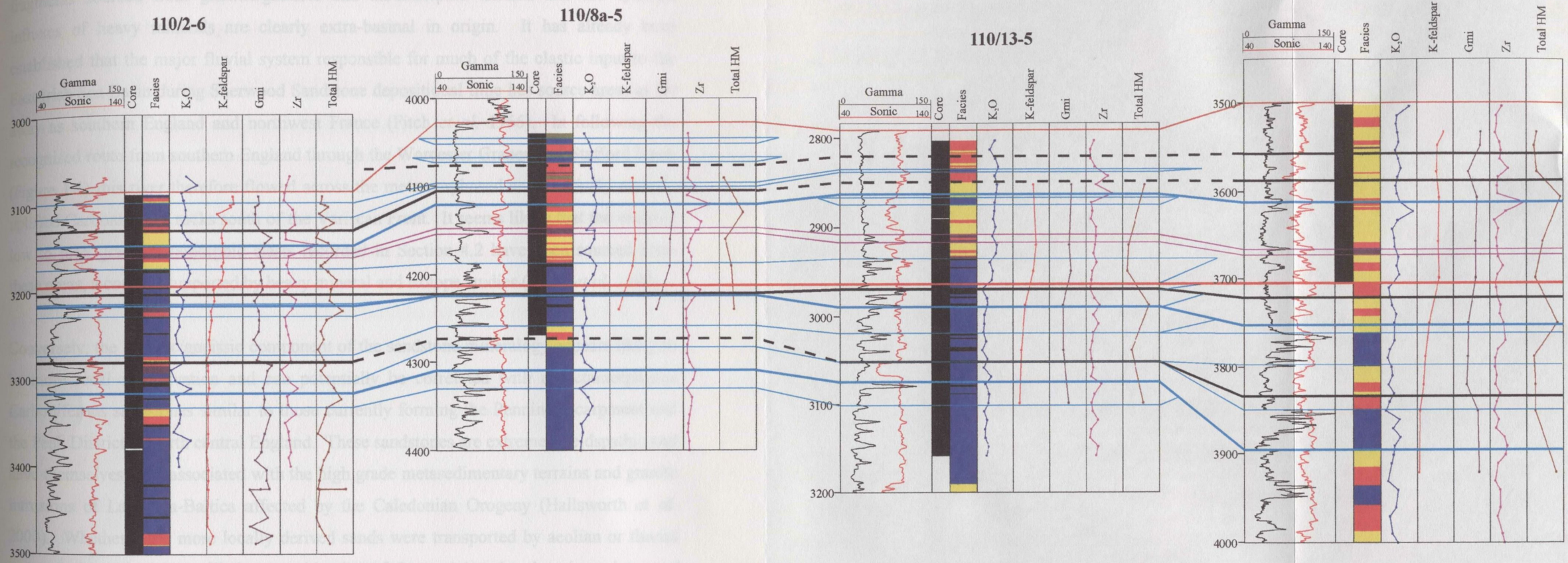


Figure 6.5 Chemical and mineralogical correlation in the upper Ormskirk Sandstone Formation showing potential fluvial channel correlations and the 'Century Playa' (datum based on the upward increase in sandstone feldspar content).

additional Sherwood Sandstone Group section present in this well that is not present in well 110/2-6 or to some extent in the other two wells.

The changes in the gross mineralogy of the sandstones, the varying proportions of rock fragments sourced from granitic/gneissic and metamorphic terrains and the episodic influxes of heavy minerals are clearly extra-basinal in origin. It has already been established that the major fluvial system responsible for much of the clastic input to the East Irish Sea Basin during Sherwood Sandstone depositional time has source areas as far away as southern England and northwest France (Fitch *et al.* 1966). In following the recognised route from southern England through the Worcester Graben and Stafford Basin (Figure 1.1) this river therefore flowed across the metamorphosed and relatively recently uplifted Carboniferous rocks south of the Variscan Front. It seems likely that the variably low to high grade metamorphic clasts recorded in Section 4.2 have been sourced form these areas, a concept supported by heavy mineral and isotope studies (Jones *et al.* 1999).

Conversely, the granitic/gneissic component of the sandstone mineralogy appears likely to be more local in derivation and can potentially be correlated with unmetamorphosed Carboniferous sandstones similar to those currently forming the Pennine escarpment and the Peak District of north central England. These sandstones are extremely feldspathic and have themselves been associated with the high grade metasedimentary terrains and granite intrusions of Laurentia-Baltica affected by the Caledonian Orogeny (Hallsworth *et al.* 2000). Whether these more locally derived sands were transported by aeolian or fluvial processes is unclear (most likely a combination of the two) but the changing mixture of these through time with the less feldspathic sands from the Variscan highlands to the south provides a means by which the varying mineralogy of the Sherwood Sandstone can be generated.

The well correlation based on the various changes in the mineralogical content of the sandstones (Figure 6.5) provides a new stratigraphic framework for these four wells that is clearly independent of the facies based approach that has guided previous Ormskirk Sandstone stratigraphies. It is apparent that the use of the upward increase in the feldspar content of the sandstones as a datum implies diachroneity at the top of the Ormskirk Sandstone and its contact with the overlying Mercia Mudstone Group. This in itself has

several implications, not least of which is the absence of Ormskirk Sandstone successions recorded in wells with a more basinal location compared to those closer to the inferred basin margin. This additional preservation of sandstone dominated successions towards the basin margin correlates closely with the increasing abundance of aeolian facies recorded in the uppermost parts of the Ormskirk Sandstone in wells 110/13-5 and 110/14-3 compared to wells 110/2-6 and 110/8a-5.

The inferred diachroneity revealed in Figure 6.5 also provides a plausible explanation for the presence of the clastic sabkha sequences preserved in the cored intervals from well 110/8a-5 (see comments in Sections 2.4 and 3.3.6). Basinwards extrapolation of these sequences based on the well correlation in Figure 6.5 implies that they are likely to be the lateral equivalents of intervals in the base of the Mercia Mudstone Group as penetrated in well 110/2-6, discussed further in Section 9.3 below. In addition, the most extensive of the preserved playa lake successions (referred to the 'Century Playa' in Section 3.4.1) appears on the new correlation to plot sub-parallel to the feldspar datum (compare Figure 2.1). Given that these playa deposits are widely recorded across the East Irish Sea Basin and are readily identifiable by being somewhat thicker and better developed than most others, its sub-parallelism to the feldspar datum provides a potential means of extending the new correlation away from the analysed wells.

Following the correlation of the chemical and mineralogical variations shown in Figure 6.5 it also becomes possible to correlate fluvial channel fills within the constraints of the tie-lines. Rather than the undivided successions of fluvial channel sandstones inherent to the well correlation in Figure 2.1, the new correlation defines both stacked amalgamated sequences of fluvial channel fills and those isolated channel fills where they are apparently surrounded and encased within sandflat and aeolian successions. It is noticeable in the present well correlation, covering only the upper parts of the Ormskirk Sandstone Formation, that stacked amalgamated sequences are prevalent in the lower parts of the correlation, while isolated channel fills are more common in the upper parts. Examples of both stacked and isolated fluvial channel fills are recorded in outcrops, most notably the stacked sequences at Helsby Hill and Hilbre Point and the isolated channels at New Brighton and Thurstaston Road Cutting. The implications of these contrasting styles of fluvial channel preservation are discussed further in Section 9.4 below.

6.4 REVISED LITHOSTRATIGRAPHY

In order to address the problems inherent in the existing lithostratigraphy of the Ormskirk, and subsequently Helsby, Sandstone Formations it is necessary to extend the well correlation presented and discussed above to achieve a near basin-wide perspective. To achieve this the sub-parallelism of the major playa sequence (referred to the 'Century Playa') to the feldspar datum used in Figure 6.5 can be applied to extend the correlation in both broadly north-south and east-west directions (Figures 6.6 and 6.7 respectively). In both cases the correspondence of wireline characteristics, especially gamma and sonic logs (as discussed in Section 2.3), has been utilised to determine the presence of fluvial channel facies outside the cored intervals. The correlation of these fluvial channel sequences between wells is constrained where applicable by the mineralogical and chemical data discussed above but is necessarily less definitive in those wells that have not undergone additional analysis.

One of the most immediate and obvious consequences of realigning the wells to take account of the new datum is the implied topography on the top Sherwood Sandstone Group to base Mercia Mudstone Group surface. This surface appears to be lowest (i.e. least vertical distance above the playa lake datum) in well 110/2-6 in Figure 6.6 and in this NNW-SSE orientated line of section it climbs both northwards and towards the southern areas of the East Irish Sea Basin from this well. The implied topography accords with models of diachroneity on this surface (Thompson and Meadows 1997 and discussion above) but appears to contradict previous assumptions regarding the presence of regional palaeoslopes from south to north in the uppermost Sherwood Sandstone Group (e.g. Meadows and Beach 1993a). The Ormskirk Sandstone Formation to Mercia Mudstone Group contact appears to exhibit palaeoslopes from both north and south into the central parts of the basin. The same surface as plotted on Figure 6.7 in which the well section is orientated broadly W-E, however, reveals a continuing westwards decrease in the vertical distance of the contact above the playa lake datum. Taken together the two well sections suggest that the regional palaeoslope during late Ormskirk Sandstone depositional time may have been towards the centre of the East Irish Sea Basin from the SE, E and NE but continuously westwards from this area towards Ireland, possibly into those areas in which remnant Sherwood Sandstone Group successions are currently preserved in the Kish Bank and Peel Basins (Figure 1.1). A syn-depositional palaeoslope in this direction would have

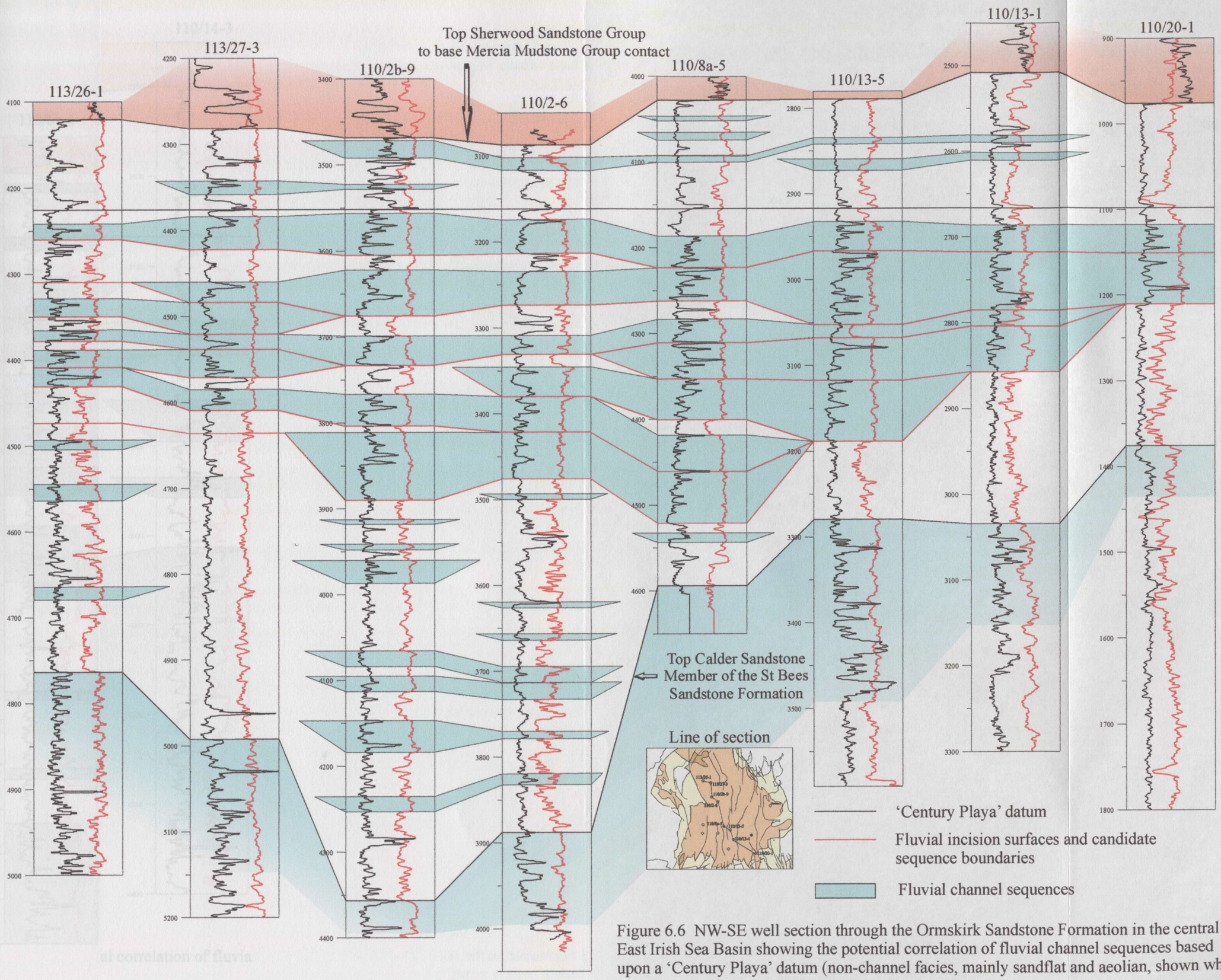


Figure 6.6 NW-SE well section through the Ormskirk Sandstone Formation in the central East Irish Sea Basin showing the potential correlation of fluvial channel sequences based upon a 'Century Playa' datum (non-channel facies, mainly sandflat and aeolian, shown white).

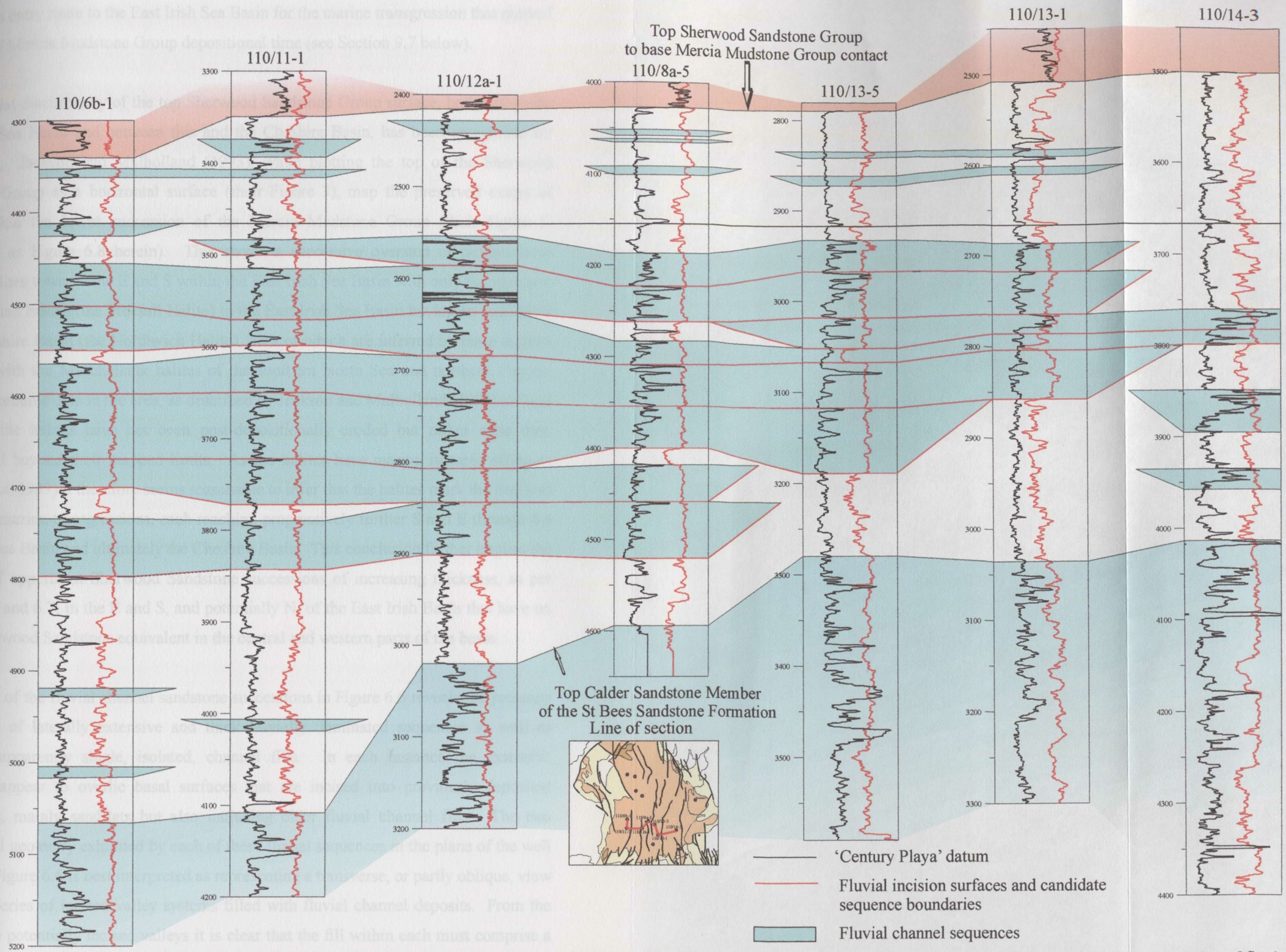


Figure 6.7 Broadly W-E well section through the Ormskirk Sandstone Formation in the south central East Irish Sea Basin showing the potential correlation of fluvia channel sequences based upon a 'Century Playa' datum (non-channel facies, mainly sandflat and aeolian, shown white).

provided both an exit route for fluvial channels during Ormskirk Sandstone depositional time and an entry route to the East Irish Sea Basin for the marine transgression that marked the onset of Mercia Mudstone Group depositional time (see Section 9.7 below).

The potential diachroneity of the top Sherwood Sandstone Group surface, both within the East Irish Sea Basin and between this and the Cheshire Basin, has been recognised for some time. Jackson and Mulholland (1993), while plotting the top of the Sherwood Sandstone Group as a horizontal surface (their Figure 3), map the preserved extent of halites within the lower succession of the Mercia Mudstone Group (their Figure 5, reproduced as Figure 6.8 herein). This shows a successive overstep of progressively younger halites towards the E and S within the East Irish Sea Basin with only the youngest of the Anisian halites (the Preesall Halite) in the East Irish Sea Basin having an equivalent in the Cheshire Basin (the Northwich Halite), both of which are inferred by these authors to equate with the Muschelkalk halites of the southern North Sea and northern Europe. Well and borehole data in the area, as described by Jackson and Mulholland (1993) make it clear that the halites have not been post-depositionally eroded but rather were non-depositional beyond their mapped limits. As the halites have marine isotopic affinities (Naylor *et al.* 1989) it therefore seems reasonable to infer that the halites mark the limits of successive marine transgressions, each reaching progressively further S and E through the East Irish Sea Basin and ultimately the Cheshire Basin. This conclusion further implies the presence of uppermost Sherwood Sandstone successions of increasing thickness, as per Figures 6.6 and 6.7, in the E and S, and potentially N, of the East Irish Basin that have no lateral Sherwood Sandstone equivalent in the central and western parts of the basin.

Correlation of the fluvial channel sandstone successions in Figure 6.6 reveals the presence of a series of laterally extensive and thick fluvially dominated sequences as well as numerous apparently single, isolated, channel fills. In each instance the extensive sequences appear to overlie basal surfaces that are incised into previously deposited successions, mainly sandflats but also including older fluvial channel fills. The two dimensional geometry exhibited by each of these fluvial sequences in the plane of the well section of Figure 6.6 is best interpreted as representing a transverse, or partly oblique, view through a series of incised valley systems filled with fluvial channel deposits. From the scale of the potentially incised valleys it is clear that the fill within each must comprise a

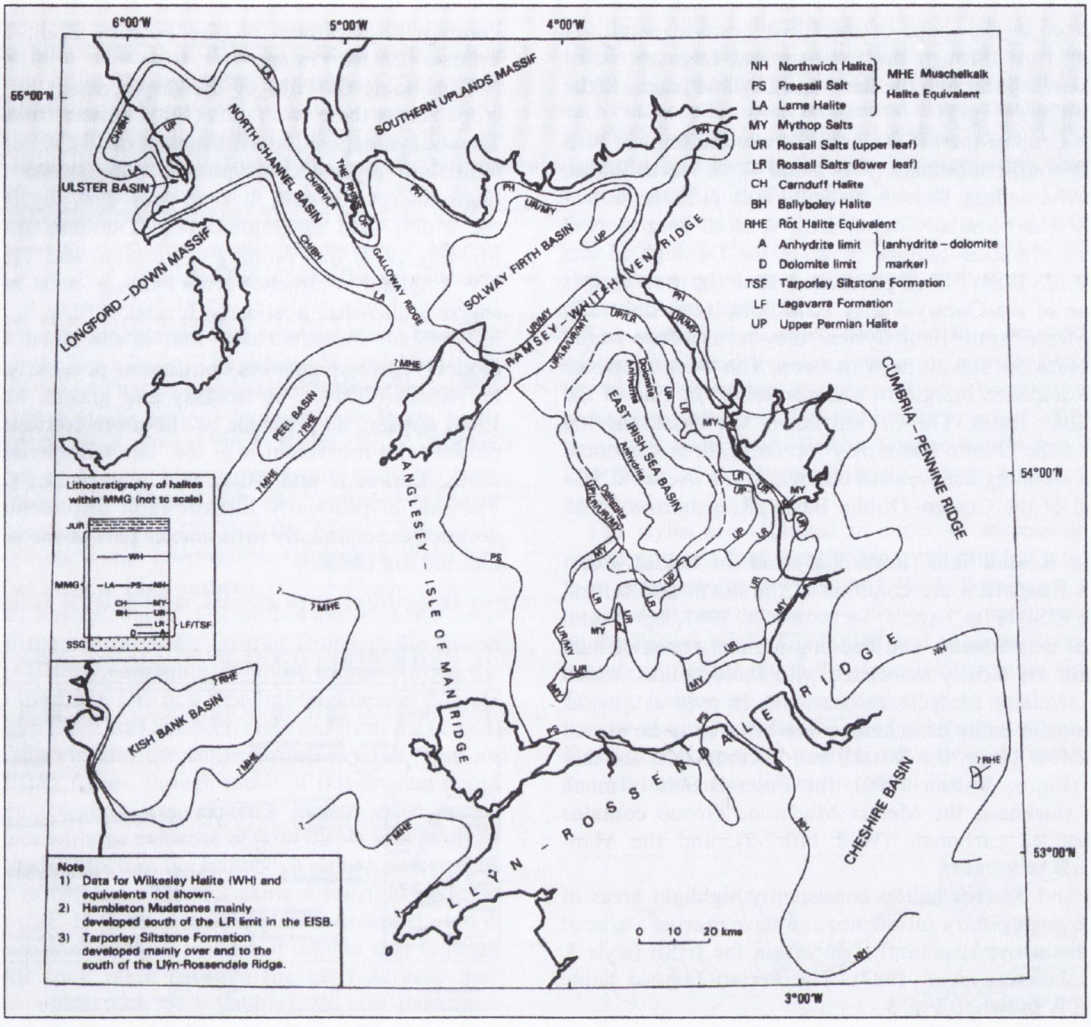


Figure 6.8 Depositional limits of halites in the Mercia Mudstone Group and Upper Permian in the East Irish Sea Basin (reproduced from Jackson and Mulholland 1993).

considerable number of individual channel fills and that these are therefore stacked and amalgamated both vertically and laterally in a manner equivalent to those recorded onshore at localities such as Helsby Hill and Carden Park. A broadly similar architecture is exhibited in the W to E well section of Figure 6.7 although, in this case, the basal incision surfaces appear to continue downcutting towards the west resulting in a progressively thicker gross fluvial package within the Ormskirk Sandstone Formation in this direction. This overall geometry would tend to suggest a more nearly longitudinal orientation for this well section, at least in its western parts, compared to the inferred transverse to oblique orientation of Figure 6.6.

The difference between the two well sections raises the possibility that, as with the suggested topography of the top Sherwood Sandstone surface, the intra-basinal palaeoslope during the deposition of the Ormskirk Sandstone Formation fluvial channels was towards the basin centre from the S and E and but then turning and continuing westwards. This supposition is supported by published palaeocurrent data based on dipmeter measurements from the Morecambe Field (Cowan 1993) which reveals broadly E to W flow directions although the spread of data includes palaeocurrents towards the NW and SE. The precise sedimentary structures measured by these data are unknown, and could therefore include aeolian bedforms as well as fluvial channel bars although, taking into account the sensitivity of dipmeter measurements at the time (the publication was based on wells drilled in the late 1970s and 1980s), it is likely that the bedforms providing the majority of the data would have been either high stage bars or relatively large aeolian dunes. Given the relative abundance of the former and paucity of the latter, especially in this near basin centre location, it is reasonable to infer that the measured data relates mainly to large bar bedforms within fluvial channels, while the spread of the palaeocurrent azimuths would conform to suggestions regarding high stage bar geometries and their oblique slipfaces as discussed in Section 3.2.1.

The conclusion that the fluvial system recorded within the Ormskirk Sandstone Formation may have exited the East Irish Sea Basin westwards, and hence across some point of the Keys Fault, contradicts previous models of fluvial channel orientations and positions controlled by faulting (Meadows and Beach 1993). It does, however, accord with inferences by Herries and Cowan (1997) regarding fluvial transport directions, based largely upon the work of Cowan *et al.* (1993), although these authors adhere to the stratigraphic layer-cake despite recognising that fluvial incision occurs across the Morecambe Field.

From the gross stratigraphic architecture of the Ormskirk Sandstone Formation as revealed in Figures 6.6 and 6.7 it is clear how a tripartite subdivision of the formation originally arose but also apparent that a simple three member layer-cake model is inappropriate and fails to account for the variability in the sedimentary facies associations. A stratigraphic formation is defined as a primary or fundamental unit of classification that should be mappable and possess some degree of internal homogeneity compared to adjacent strata

(Holland 1978; Rawson *et al.* 2002). From the foregoing discussion it is apparent that the Ormskirk and Helsby Sandstone Formations do not currently meet these criteria and it becomes questionable, given the degree of heterogeneity in the upper Sherwood Sandstone Group succession, that they ever can. The sparse sedimentological data available from the Calder Member of the St Bees Sandstone Formation and from the Wilmslow Sandstone Formation, together with that inferred from wireline log characteristics, indicates that facies associations are no different there to those recorded in the Ormskirk and Helsby Sandstone Formations (see Section 7 below) and the confusion surrounding the definition of boundaries between them would support this conclusion.

Although the upper part of the Sherwood Sandstone Group does not appear to conform to concepts of hierarchical stratigraphic definition, this does not imply that subdivision is not possible. The candidate sequence boundaries, defined by prominent fluvial incision surfaces as highlighted in Figures 6.6 and 6.7, provide a means of re-defining the stratigraphy of the succession. There are at least seven, and arguably eight or more, of these within the succession currently defined as the Ormskirk Sandstone Formation in the East Irish Sea Basin and, within the limits of the present study and well availability, each of these can be correlated across a significant area of the basin. If each of these surfaces is taken as the lower bounding surface to a sequence that includes both fluvial and sandflat/playa facies associations, with the upper bounding surface being defined by the next incision surface above or its correlative conformable surface within the sandflats, then at least nine and possibly 10-12 such sedimentary packages can be identified between the presumed top of the Calder Sandstone Member and the base of the Mercia Mudstone Group (Figure 6.6 and 6.7).

These packages are potentially mappable and conform to the definition of a sequence as described by Mitchum (1977), later elaborated by van Wagoner *et al.* (1990), as 'a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities.' In this context, it is noticeable that not all stacked and amalgamated fluvial channel sequences extend across the whole basin, or even the full extent of the well sections in Figures 6.6 and 6.7. It is therefore likely, in fact almost certain, that there are surfaces (effectively bedding planes) within the sandflat successions

that are the conformable correlative and time equivalent of the basal incision surfaces defining the stacked amalgamated fluvial channel fills forming the correlatable sequences.

The stratigraphic distribution of the sequences, as defined and briefly commented upon above, reveals a tendency towards isolated channels in the uppermost and lowermost parts of the Ormskirk Sandstone Formation and a concentration of apparently more deeply incised and thickly preserved fluvial channel-dominated sequences through the central parts of the formation. While the generalization of this stratal architecture has clearly given rise to the tri-partite nomenclature inherent in the presently accepted stratigraphy, it is equally clear that the succession records a significant waxing and waning in the dominance and/or preservation of fluvial channel fills, an aspect discussed further in Section 9.4 below.

The identification of the stratal architecture described for the Ormskirk Sandstone Formation raises the question of whether similar characteristics can be identified both in the underlying Calder Member of the St Bees Sandstone Formation (discussed in Section 7 below) and in the broadly correlative Helsby Sandstone Formation of the Cheshire Basin. In the latter case evidence is sparse as only three out of the six available wells penetrated to the presumed base of the Helsby Sandstone (Burford-1, Knutsford-1 and Prees-1) and these are widely separated (Figure 1.4). It is still feasible to erect a well correlation based upon the six available wells but care must be exercised in drawing conclusions from any inferred distribution of facies associations. The problem of a suitable datum, in the absence of core, mineralogical or chemical data, is not easily overcome. It is apparent from previous discussions on the East Irish Sea Basin that the top Sherwood Sandstone Group to base Mercia Mudstone Group contact is unlikely to provide a meaningful datum although this has been used by other authors (e.g. Warrington *et al.* 1999), while some have preferred the base of the first major halite within the Mercia Mudstone Group (e.g. Mikkelsen and Floodpage 1997). Problems inherent in both of these are compounded by the nature of the lowermost Mercia Mudstone Group succession in the Cheshire Basin which becomes progressively more silty southwards and also includes interdigitated sandstones that vary in number and thickness (the Malpas sandstone of Warrington *et al.* 1980).

The sedimentary facies associations encountered in the Cheshire Basin wells can be determined using the wireline log characteristics as previously carried out for the East Irish Sea Basin wells (Section 2.3 and Figures 6.6 and 6.7). While this exercise readily identifies broadly fluvial and sandflat facies associations it does not satisfactorily determine facies such as playa lake or playa margin and, given the limited playa related facies from outcrops within the Sherwood Sandstone Group succession in the Cheshire Basin, they cannot be assumed to be extensive and therefore used as an alternative datum. The exercise does, however, provide an alternative datum for well correlation in that it becomes apparent there are major stacked and amalgamated fluvial channel sandstones preserved in these wells at a broadly similar stratigraphic level, conforming to the Delamere Sandstone Member, to that of the East Irish Sea Basin (Figure 6.9). Although not entirely satisfactory, the tops of these amalgamated fluvial channel successions can be used as a datum in a manner similar to that employed by Thompson and Meadows (1997) in the East Irish Sea where, although subsequently refined by the present study, this surface did provide evidence for top Sherwood Sandstone diachroneity and an early attempt at a more realistic correlation of fluvial channel sequences.

The datum used in Figure 6.9 coincides with the top of the Delamere Sandstone Member as generally shown on well Composite Logs and in the well sections in Appendix I. It is of note that the suggested correlation again indicates considerable relief on the top Sherwood Sandstone to base Mercia Mudstone Groups surface similar to that revealed in the East Irish Sea Basin sections (Figures 6.6 and 6.7) with an implied topography that falls from the Knutsford-1 well south to Boots Green-1 and then rises again southwards. The correlation into the Prees-1 well must be viewed with some reservation, due both to the distance SW from Blakenhall-1 to this well (some 13kms) and also to the relatively poor quality of the wireline data as reproduced from Warrington *et al.* (1999). Notwithstanding this the remaining wells reveal a similar pattern of distribution, both areal and stratigraphic, for the stacked amalgamated and isolated fluvial channel sequences to that proven in the East Irish Sea Basin and it seems reasonable to infer that corresponding sequence boundaries related to fluvial incision may well be present in the Cheshire Basin.

This conclusion is reinforced by examination of the work originally undertaken to erect the subdivisions of the Helsby Sandstone Formation (Thompson 1970). One of the critical

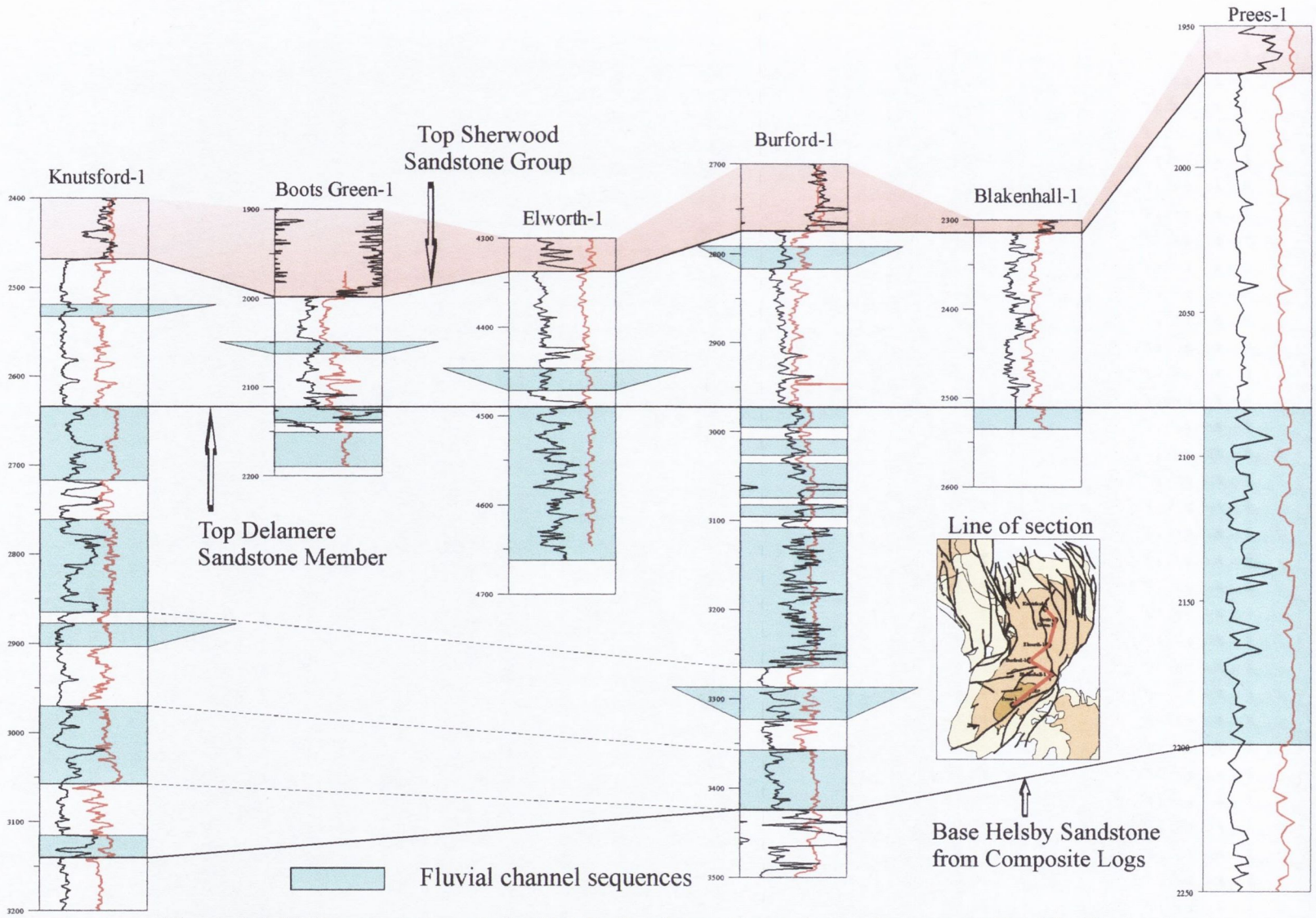


Figure 6.9 Well section through the Helsby Sandstone Formation in the central Cheshire Basin showing potential correlation of fluvial channel sequences based upon a top major fluvial succession datum (non-channel facies, mainly sandflat and aeolian, shown white).

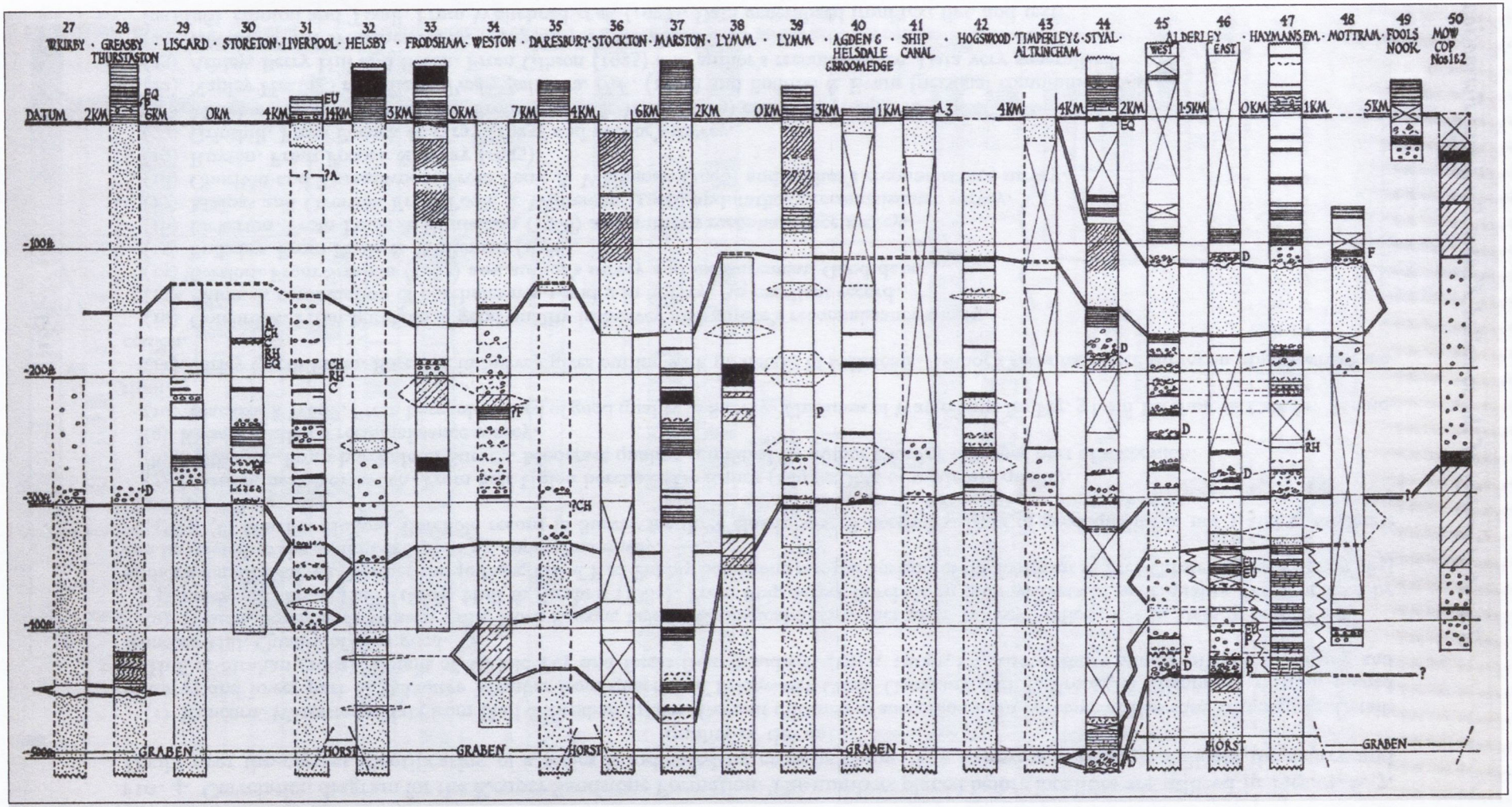


Figure 6.10 Correlation of facies associations between boreholes from the Wirral Peninsular on the left across the northern parts of the Cheshire Basin to the hangingwall of the Red Rock Fault south of Manchester on the right (reproduced from Thompson 1970).

diagrams used to determine the lateral and stratigraphic extent of the Frodsham, Delamere and Thurstaston Members (Figure 5 in Thompson 1970) is reproduced here as Figure 6.10 and is based on the facies correlation of 24 shallow boreholes forming a section from West Kirby on the Wirral Peninsular across the northern Cheshire Basin to the proximity of the Red Rock Fault south of Manchester. With the benefit of hindsight this diagram clearly reveals the interdigitation of fluvial and sandflat facies and the potential incision on the base of stacked amalgamated fluvial channel sequences.

The base of the Delamere Sandstone Member has been re-interpreted as the base of the Helsby Sandstone Formation in some publications from BGS since a re-examination of the succession in the Chester area (Earp and Taylor 1986), most notably by Warrington *et al.* 1999). The possibility that this surface may represent an unconformity has been taken up by several authors, including Evans *et al.* (1993) in a re-assessment of the structural evolution of the Cheshire Basin, who identified an intra-Sherwood Sandstone angular unconformity from seismic data that they related to the Hardegsen Unconformity of the southern North Sea and onshore NW Europe. According to these authors some 200-220m of section, unpenetrated by boreholes, is cut out below the unconformity although they maintain that as much as 850-900m of strata may be locally absent. Figure 8 (reproduced herein as Figure 6.11) in Evans *et al.* (1993) does appear to reveal truncation within the

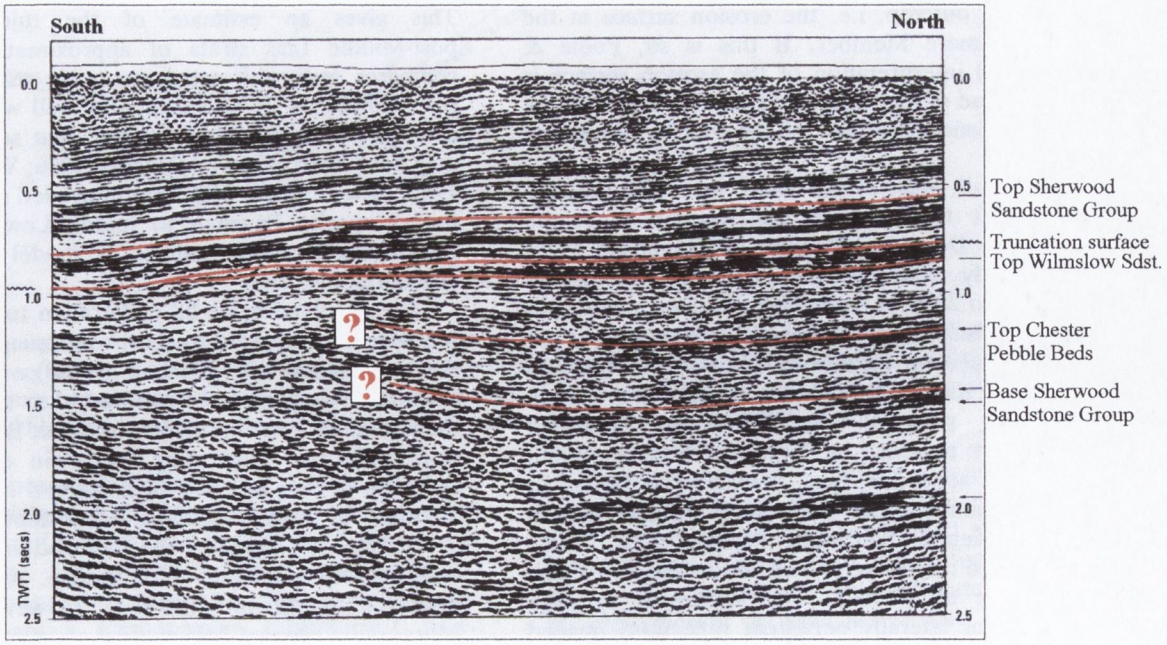


Figure 6.11 Seismic reflection line suggested to show intra-Sherwood Sdst. truncation interpreted as the Hardegsen Unconformity (reproduced from Evans *et al.* 1993).

Sherwood Sandstone but reference to their map of seismic line locations shows that this particular line is aligned sub-parallel to the Red Rock/Wem Fault System approximately 3kms to the west of the Blakenhall-1 well location. There is no evidence of intra-Sherwood truncation on any of the other seismic lines reproduced, most notably those that are orientated nearly normal to the fault.

It seems likely that, had significant uplift occurred during Sherwood Sandstone depositional time, the Red Rock/Wem Fault, as the largest syn-Sherwood structure in the basin, would have accommodated at least some of the shortening by means of hangingwall inversion. The only seismic line shown by Evans *et al.* (1993) that intersects this system (their Figure 9) shows, both in the section and their interpretation of it, no hangingwall inversion but does reveal considerable syn-sedimentary thickening across a subsidiary fault parallel to the Wem Fault. Two alternative interpretations of the apparent truncation shown in Figure 6.11 can be suggested. The first concerns the precise location of the line shown in this figure which intersects that shown in their Figure 9 by Evans *et a*l. (1993) and, hence, raises the possibility that this line has also intersected the fault across which syn-sedimentary thickening is apparent. This would account for the difficulty in tracing the top Chester Pebble Beds Formation and base Sherwood Sandstone Group surfaces southwards as the majority of the thickening is recorded in the pre-Helsby Sandstone succession. However, it is also possible that this line has intersected the margin of an incised valley system similar to those revealed in the East Irish Sea Basin by Figure 6.6. It is noticeable that incised valleys tend to be stacked vertically or adjacent to each other such that, as shown by the cumulative relief on the basal surfaces running from well 110/8a-5 through 110/13-5 and 110/13-1 to 110/20-1 in Figure 6.6, a considerable vertical succession of sandflats can be preserved at the margins of the system, while stacked fluvial channel sequences form the lateral equivalent (above the cumulative incision surfaces) towards the centre.

If the latter explanation for the apparent truncation shown on the seismic line in Figure 6.11 has any validity, then the orientation of the line sub-parallel to the Red Rock Fault would indicate a fluvial system flowing towards the W or NW from the faulted eastern margin of the basin and hence towards the basin centre. This would accord with locations such as Red Hills which record the position of fluvial entry points to the basin across the

Hodnet Horst by north westwards flowing rivers and with the preserved location of stacked fluvial channel deposits forming the crest of the present-day line of hills running from Helsby Hill south to Bickerton through the west central parts of the Cheshire Basin. No comparable fluvial channel sequences are preserved, or at least exposed, either N or S of these outcrops and they appear to mark the preserved limits of a fluvial channel belt some 20kms wide in which the majority of sedimentary structures indicate palaeoflow to the NW (an aspect discussed further in Section 9 below).

7. CALDER AND WILMSLOW SANDSTONES

7.1 INTRODUCTION

The Calder Sandstone Member of the St Bees Sandstone Formation in the East Irish Sea Basin and the Wilmslow Sandstone Formation in the Cheshire Basin are taken to be equivalent, despite their different standing in the stratigraphic hierarchy. They jointly form the middle unit of the Sherwood Sandstone Group in the two basins and are deemed to be recognisable and identifiable stratigraphic units (Jackson *et al.* 1997; Warrington *et al.* 1999). Although evidence is sparse, there is very little core recovery from this succession in the offshore areas and limited outcrop onshore, that which is available would indicate comparable sedimentary facies to those described for the Ormskirk and Helsby Sandstone Formations.

The definition of the top of the Calder and Wilmslow Sandstones is essentially the problem of the definition of the base of the Ormskirk and Helsby Sandstone Formations (discussed above) and must therefore, for the moment, be left unresolved. Picking of the base is, however, somewhat more easy in that it has been traditionally taken at a prominent gamma and sonic log break recognised in the majority of wells that penetrated to this depth (see Section 2.3).

7.2 SUBDIVISIONS

Formal subdivision of the Calder Member of the St Bees Sandstone Formation has only been attempted by Jackson and Johnson (1996) and Jackson *et al.* (1997) who were initially responsible for the definition and formal recognition of the member. These authors recognised four informal units (Figure 1.2) within the Calder Member (termed CR1 to CR4 from base to top) based upon wireline log responses in three wells; 110/6b-1, 110/13-1 and 113/27-1 (the latter well has not been made available to the present study). No subdivision of the Wilmslow Sandstone Formation has been proposed.

The Calder Sandstone Member subdivisions are characterized essentially by alternating successions of high gamma, low sonic and low gamma, high sonic sandstones that, by analogy with similar successions in the Ormskirk Sandstone Formation are interpreted by Jackson *et al.* (1997) as comprising fluvially dominated and sandflat dominated

successions respectively. Similar characteristics can be recognised in wells 113/27-3 and 110/2b-9 (Figure 7.1) and in wells 110/11-1 and 110/12a-1 (Figure 7.2) suggesting that the informal subdivision of the Member can be carried across a significant area of the East Irish Sea Basin. Careful examination of the wireline logs for those wells that penetrated all or much of the Calder Member (see Appendix I) however, reveals that the subdivision is difficult, if not impossible, to carry into wells located in the southern and south eastern parts of the East Irish Sea Basin. This includes well 110/13-1 which was used by Jackson and Johnson (1996) to both define the Calder Member and its subdivisions but which, on closer inspection, does not include a definitive middle fluvial unit (equivalent to CR2) that would serve to extend the correlation to this area.

Data in the Cheshire Basin is even more sparse with only two wells, Knutsford-1 and Prees-1, that penetrated to the base of the Wilmslow Sandstone Formation. In both cases, however, and in the absence of any core, there is nothing in the log responses that would facilitate any subdivision of the formation. The character of the gamma and the sonic logs through the Wilmslow Sandstone Formation in both wells would appear to preclude the presence of any fluvial channel sequences and, with their relatively low gamma and high sonic velocity, would suggest relatively thick successions dominated by sandflat facies associations. The sparse outcrop data from the Wilmslow Sandstone Formation (see logs for Moss Farm in Appendix II) indicates that fluvial channels are present but that these tend to be isolated and do not form the stacked amalgamated sequences typical of the Delamere Member of the Helsby Sandstone Formation. In contrast, the limited data available from the Burford-1 well (Appendix I) which penetrated some 160m into the Wilmslow Sandstone Formation, appears to exhibit a log character in the upper parts of the formation that would suggest stacked fluvial channel sandstones are present in this area.

7.3 REVISED CORRELATIONS

The sparse well data, and absence of mineralogical and chemical data from either the Calder Member or the Wilmslow Sandstone Formation renders any revised well correlation extremely speculative. The principal problem, as with other successions in the Sherwood Sandstone Group, is the objective definition of a suitable datum with which to attempt a correlation of the major facies associations and, particularly, the stacked

amalgamated fluvial channel sequences that are clearly the key to an understanding of stratal architecture.

Following the example cited above for the revised correlation of the Helsby Sandstone Formation in the Cheshire Basin, Figures 7.1 and 7.2 use for a datum the top of the prominent fluvial channel succession (CR4 of Jackson and Johnson 1996) that defines the top of the Calder Member in the East Irish Sea Basin. While it is recognised that this surface is highly unlikely to be synchronous and the orientation and amount of any diachroneity are unknown, it does provide the only readily identifiable log pick that can be recognised in all the available wells. It is of particular note that, when correlated across the basin, the stacked amalgamated fluvial channel succession forming this uppermost part of the Calder Member exhibits a geometry remarkably similar to that of the incised valley sequences defined in the Ormskirk Sandstone Formation and described above (Sections 6.3 and 6.4). If the base of this succession does indeed mark an episode of fluvial incision, followed by aggradation and infilling of the incised valley system, then it is apparent that it has an orientation similar to that of the corresponding systems within the Ormskirk Sandstone. The broadly NNW to SSE section of Figure 7.1 reveals a transverse or oblique section with incision deepest in the vicinity of wells 113/27-3 and 110/2b-9, while the broadly W to E section of Figure 7.2 appears to show continued downcutting towards the W with deepest incision at the well 110/6b-1 location. This would imply that, as with incised valley fills higher in the Sherwood Sandstone Group, this particular system flowed towards the NW across the central parts of the basin but then turned westwards to exit the East Irish Sea Basin south of the Isle of Man.

The definition and extent of the lower fluvially dominated succession within the Calder Sandstone Member (equivalent to CR2) is even more problematical. The wireline log character for this interval in wells located in the western parts of the East Irish Sea Basin appear to unequivocally suggest the presence of a significant and thick succession of stacked fluvial channel sandstones in these areas. In this context, the lack of log data over this interval from the 113/26-1 well is particularly unfortunate. There are corresponding but relatively thin fluvial intervals identifiable in wells 110/14-3 and 110/20-1 (Figures 7.1 and 7.2) but whether these form parts of the same system or are merely precursors to the

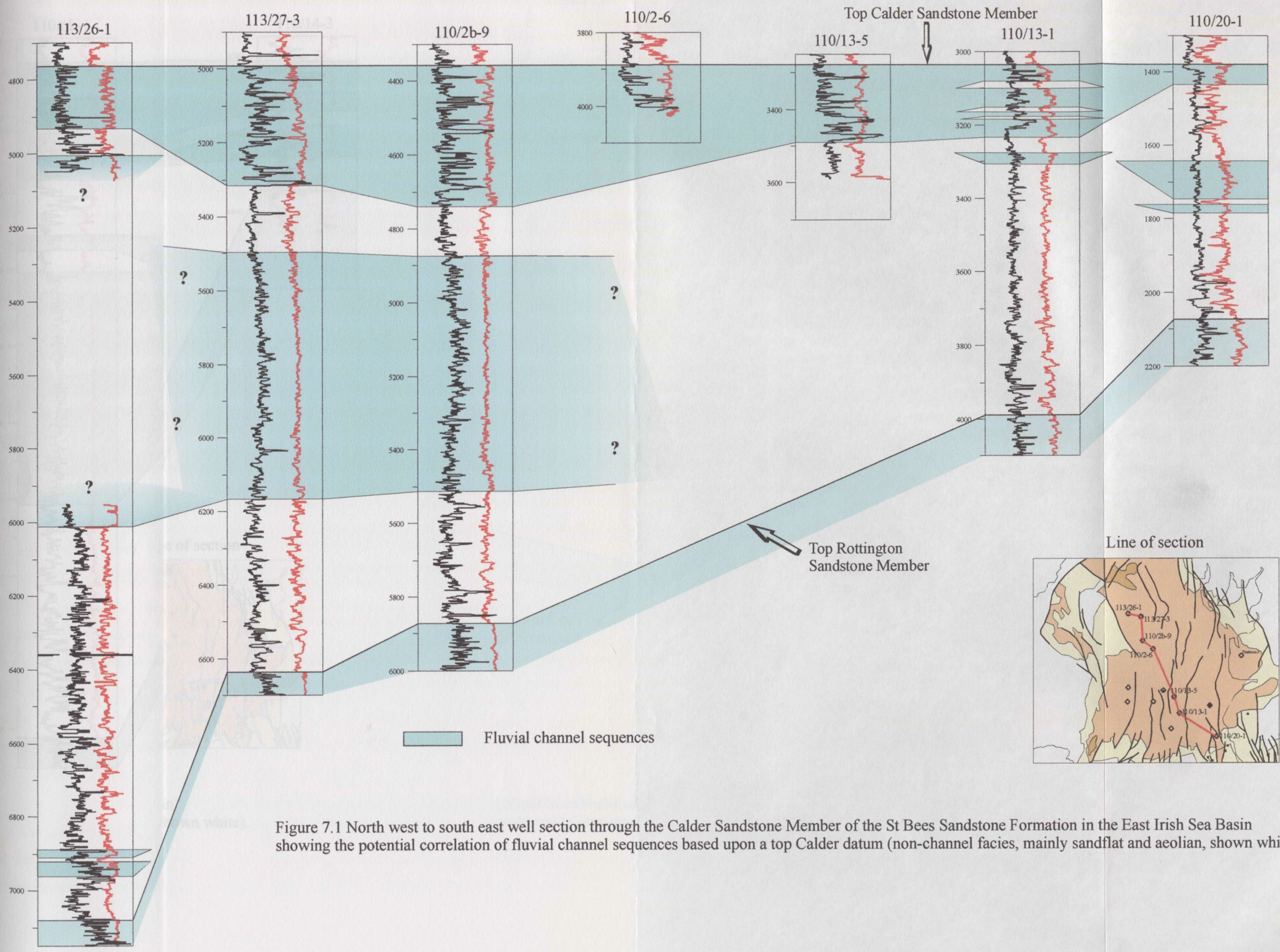


Figure 7.1 North west to south east well section through the Calder Sandstone Member of the St Bees Sandstone Formation in the East Irish Sea Basin showing the potential correlation of fluvial channel sequences based upon a top Calder datum (non-channel facies, mainly sandflat and aeolian, shown white).

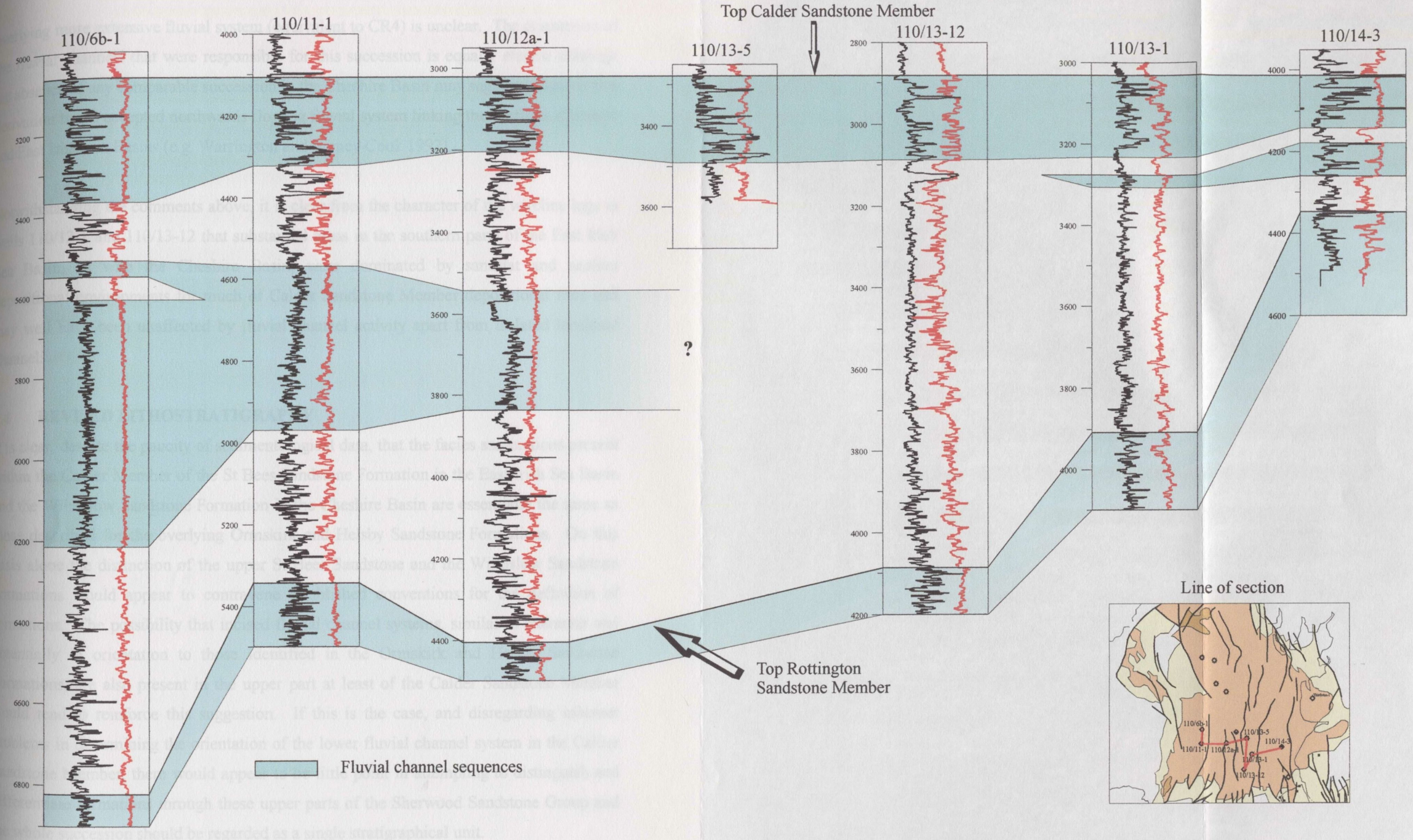


Figure 7.2 Broadly west to east well section through the Calder Sandstone Member of the St Bees Sandstone Formation in the East Irish Sea Basin showing the potential correlation of fluvial channel sequences based upon a top Calder datum (non-channel facies, mainly sandflat and aeolian, shown white).

overlying more extensive fluvial system (equivalent to CR4) is unclear. The orientation of the fluvial channels that were responsible for this succession is equally elusive although the absence of any comparable succession in the Cheshire Basin may suggest an alternative derivation to the accepted northwards flowing fluvial system linking the Stafford, Cheshire and East Irish Sea Basins (e.g. Warrington and Ivimey-Cook 1992).

Notwithstanding the comments above, it is clear from the character of the wireline logs in wells 110/13-1 and 110/13-12 that substantial areas in the southern parts of the East Irish Sea Basin, as with the Cheshire Basin, were dominated by sandflat and aeolian depositional environments for much of Calder Sandstone Member depositional time and may well have been unaffected by fluvial channel activity apart from isolated localized channels.

7.4 REVISED LITHOSTRATIGRAPHY

It is clear, despite the paucity of sedimentological data, that the facies associations present within the Calder Member of the St Bees Sandstone Formation in the East Irish Sea Basin and the Wilmslow Sandstone Formation in the Cheshire Basin are essentially the same as those described for the overlying Ormskirk and Helsby Sandstone Formations. On this basis alone the distinction of the upper St Bees Sandstone and the Wilmslow Sandstone Formations would appear to contravene established conventions for the definition of formations. The possibility that incised fluvial channel systems, similar in character and potentially in orientation to those identified in the Ormskirk and Helsby Sandstone Formations, are also present in the upper part at least of the Calder Sandstone Member would tend to reinforce this suggestion. If this is the case, and disregarding inherent problems in determining the orientation of the lower fluvial channel system in the Calder Sandstone Member, there would appear to be little point in attempting to distinguish and differentiate formations through these upper parts of the Sherwood Sandstone Group and the whole succession should be regarded as a single stratigraphical unit.

Despite the difficulties of satisfactorily identifying and satisfactorily correlating facies associations within the Calder and Wilmslow Sandstones, the presence of sequences and candidate sequence boundaries can be implied from the available data. On this basis it is

feasible that a similar architecture to that suggested for the Ormskirk and Helsby Sandstones exists within the Calder and Wilmslow Sandstones. The definition of sequences in this part of the succession is necessarily somewhat more crude than in the overlying units but it is likely that, were the same level of data available, then the heterogeneity of the stratal architecture would closely approach that of the Ormskirk and Helsby Sandstones as discussed above.

8. ROTTINGTON AND CHESTER PEBBLE BEDS SANDSTONES

8.1 INTRODUCTION

As with the overlying Calder and Wilmslow Sandstones, the Rottington Member of the St Bees Sandstone Formation in the East Irish Sea Basin and the Chester Pebble Beds Formation in the Cheshire Basin are taken to be lateral equivalents. Also similarly, there is no available core from either of these successions but, unlike the overlying Calder and Wilmslow Sandstones, there are extensive outcrops of the Rottington Member in west Cumbria where coastal cliffs, although not easy to access, can be examined for more than 5kms from Saltom Bay around St Bees North and South Heads and the intervening Fleswick Bay into St Bees Bay. Gentle dips to the south have facilitated the sedimentological logging of more than 160m of vertical section from these cliffs, while outcrops of the Chester Pebble Beds Formation around Wirral and Chester have provided a further 114m of logged vertical section. All the available evidence indicates that both the Rottington Member and the Chester Pebble Beds Formation are almost entirely fluvially dominated, the only exception being facies recorded at the base of the succession in west Cumbria (discussed below), and that sandflat and floodplain related facies are absent. Concepts introduced and discussed above regarding the interdigitation of fluvial channel and sandflat or floodplain facies, and the stratal architecture of the upper Sherwood Sandstone Group that devolves from this relationship, are therefore not applicable to these lower parts of the succession.

8.2 EXISTING CORRELATIONS

Few, if any, detailed correlations of the lower Sherwood Sandstone Group have been attempted. The succession is too deep, lying at the base of what is commonly more than a kilometre of sandstone dominated rocks, to be of interest to the hydrocarbon industry, and is effectively written off as a 'thick monotonous orthoquartzitic sandstone' by those more concerned with the stratigraphy (Jackson *et al.* 1997). Where the top and the base of the Rottington Member or the Chester Pebble Beds Formation are shown in publications they are generally represented as simple linear contacts, often horizontal, to the overlying Calder Member and Wilmslow Sandstone Formation respectively or to the underlying, presumed Permian, Barrowmouth Mudstone Formation, Freshfield Sandstone Member or Kinnerton Sandstone Formation depending on the location.

The upper boundaries of the Rottington Member and the Wilmslow Sandstone Formation are commonly referred to as the 'top Silicified Zone' following Colter and Barr (1975) who recognised a surface that could be identified on seismic and wireline data due to a sharp downward increase in sonic velocities. The silicification was ascribed to diagenetic effects consequent on the argillaceous nature of the succession (suggested by the high gamma log response although this is probably more a consequence of the extremely high K-feldspar content of the sandstones, ranging up to 16.5%; see modal data in Appendix III) and presumed depth of burial (Ebbern 1981). The nature of this boundary, as being partly lithological and partly diagenetic, appears to have been widely and unquestioningly accepted with similar views expressed by numerous authors (e.g. Jackson *et al.* 1987; Jackson and Mulholland 1993; Evans *et al.* 1993). With the recognition that sedimentary facies to some extent control diagenetic processes in the Sherwood Sandstone Group, specifically the fluvial facies preference of silica cements (Meadows and Beach 1993b) it became appreciated that the 'top Silicified Zone' was in all probability equivalent to the top of the c. 400m thick stacked fluvial channel succession in west Cumbria that is now recognised as the Rottington Member and that wireline log picks correspond with the facies break to overlying, less cemented, sandflat facies of the Calder Member.

The nature and geometry of the basal boundary has never been seriously questioned despite having been variously defined as the contact with the Barrowmouth Mudstone Formation in the northern East Irish Sea Basin (Jackson *et al.* 1997), with the Freshfield Sandstone Member in the southern parts (Jackson *et al.* 1997) and with the Kinnerton Sandstone Formation in the Cheshire Basin (Warrington *et al.* 1999).

8.3 BASE OF THE SHERWOOD SANDSTONE GROUP

Examination of outcrops and wireline logs from those wells that penetrate to the base of the Rottington Sandstone Member and the Chester Pebble Beds Formation, and hence the base of the Sherwood Sandstone Group, makes it clear that the character of this boundary changes significantly both between the Cheshire and East Irish Sea Basins and across the basins (see Section 2.3).

In reality this basal succession of the Sherwood Sandstone Group is far from simple, as shown by outcrops in west Cumbria where the repeated interbedding of sandstones,

siltstones and claystones over a considerable vertical distance makes any definition of a base to the group extremely speculative (see discussion in Sections 2.3 and 3.6). The highly feldspathic nature of the sandstones forming the Rottington Member, mentioned above, makes the distinction of sandstone and claystone lithologies in wells difficult from wireline data alone. The base of the Sherwood Sandstone has therefore tended to be defined by a direct correlation of the base of the lowest identifiable sandstone in the northern East Irish Sea Basin with the more readily picked contacts where the Sherwood Sandstone overlies the Freshfield Member and the Kinnerton Sandstone Formation. This correlation leads to a dramatic northwards thickening in the Barrowmouth Mudstone which is not easily explained in terms of its favoured interpretation as a ?marginal marine/coastal plain succession (Macchi 1988). This interpretation is, however, loosely based on the association of the mudstones with the underlying St Bees Evaporites Formation that are undeniably marine carbonate shoal to marginal marine evaporite sequences (Arthurton and Hemingway 1972). Add to this the absence of distinctive marine facies from the Barrowmouth Mudstone Formation and a complete dearth of biostratigraphical evidence (Warrington and Ivimey-Cook 1992), which would be expected had the formation been of marginal marine origin, and it is clear that the onset of Sherwood Sandstone deposition requires re-examination.

8.4 REVISED CORRELATIONS

As is the case with rocks higher in the Sherwood Sandstone Group succession, the basic problem of identifying a suitable datum is critical in attempting to understand the lithostratigraphy of the Barrowmouth Mudstone/Freshfield Sandstone transition upwards into the Sherwood Sandstone. The interdigitation of sandstones and claystones in west Cumbria, and the re-interpretation of the claystones as lacustrine fines (Section 3.4.1), clearly render the base of any of the many individual sandstones ineligible as a useful datum. In the absence of any biostratigraphical marker within either the claystones or the sandstones, and in the absence of chemical data or a sufficiently comprehensive petrographical database, the only other dependable surface is that provided by the top of the Late Permian evaporites in the northern and central areas of the East Irish Sea Basin. Southwards and into the Cheshire Basin these evaporites thin and disappear to be replaced by the Manchester Marl Formation but in these areas the base of the almost entirely fluvial Rottington Member and Chester Pebble Beds Formation are more clearly defined.

The contact at the top of the evaporites is easily picked in those wells that have penetrated to this stratigraphic level (Figure 8.1) and hence at least provides a recognisable surface from which to attempt a well correlation. Examination of the cuttings description information supplied on the Composite Logs for the wells included in Figure 8.1 reveals a similar interbedding of silty and argillaceous sandstones with the claystones of the Barrowmouth Mudstone Formation to that observed in west Cumbria (see logged section for Saltom Bay; Appendix II). The sandstones are both more abundant and thicker in the southern wells than in the northern parts of the basin and tend to become thicker and more numerous upwards through each of the well sections examined. The attempt to correlate these sandstones shown in Figure 8.1 is somewhat schematic and clearly not a unique solution. It does, however, demonstrate the northwards progradation of the sandstones, a direction that is consistent with palaeo-flow data from the Chester Pebble beds Formation on the Wirral and from the Rottington Member in west Cumbria (see logged sections for Bromborough Beach and Fleswick Bay/St Bees South Head and comments in Section 3.6).

It seems likely that much of the northern and central East Irish Sea Basin, prior to the development of a through going fluvial system, was occupied by a laterally extensive, if potentially ephemeral, lake. The establishment of a northwards flowing river system, draining from southern and central England through the Cheshire Basin and into the East Irish Sea Basin, transporting with it large volumes of sand and fines, would have both fed the lake with water and begun to fill it in from the south northwards. The stratal geometry depicted in Figure 8.1 suggests repeated episodes of lacustrine fluvio-deltaic progradation followed by flooding and transgression of the lake over the previously deposited sands. In addition, the individual progradational units appear to be stacked in a manner that bears comparison with the idealised parasequence sets of Van Wagoner *et al.* (1990) despite the fact these authors were describing marginal marine sandstones (see discussion below in Section 9.6 and Figure 8.1). In this context at least four and probably five progradational parasequence sets can be recognised in the succession from top St Bees Evaporites Formation through the Barrowmouth Mudstone Formation and the transition into undeniable Sherwood Sandstone Group

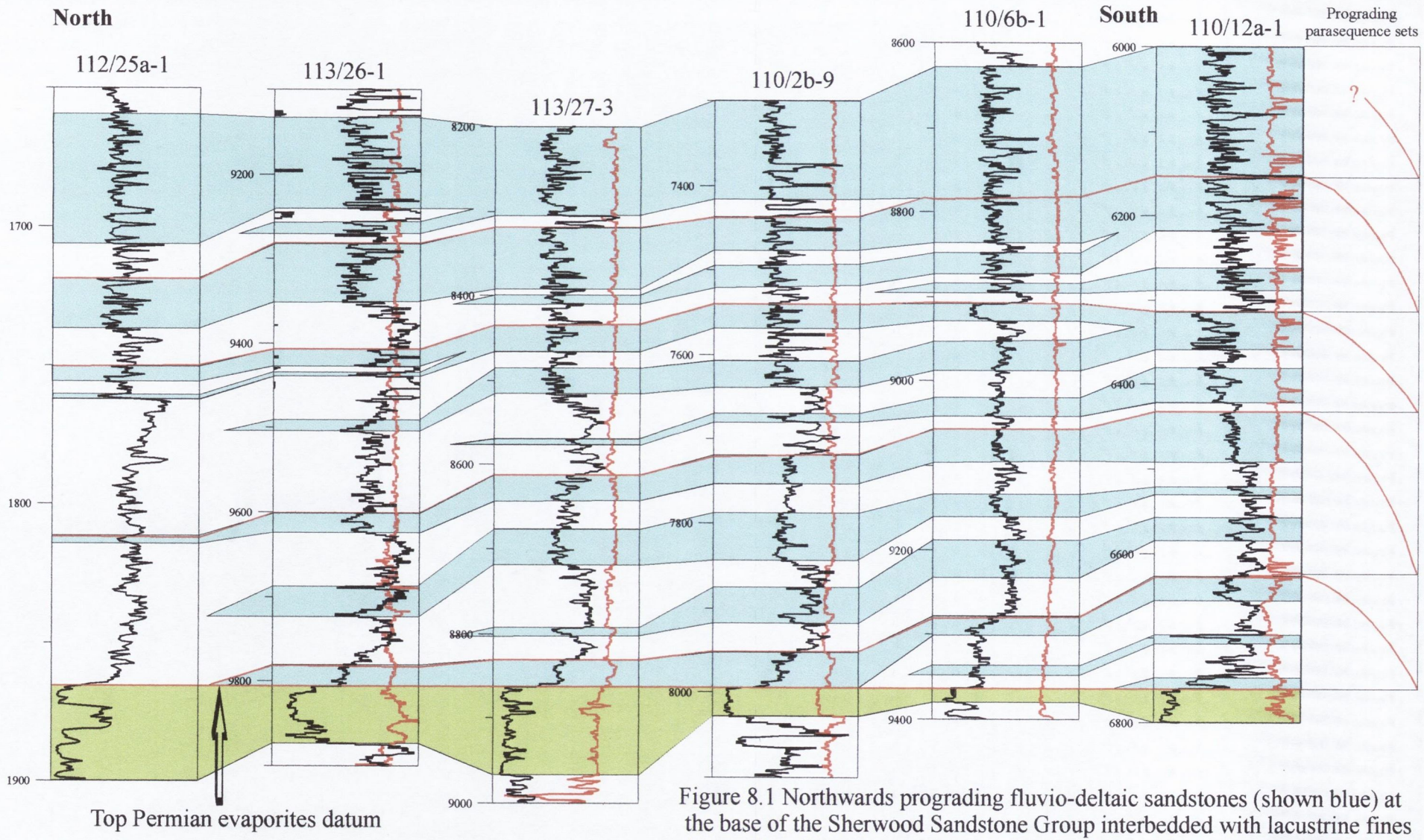
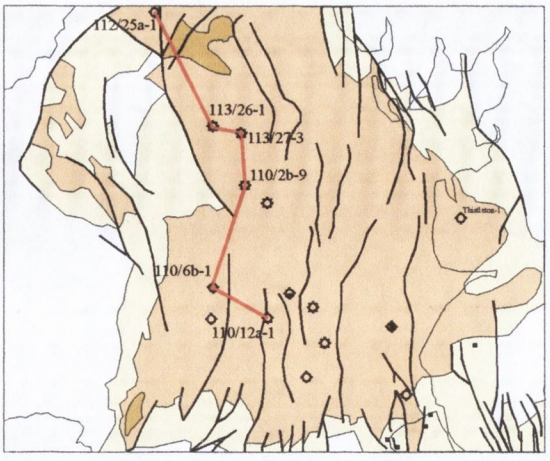


Figure 8.1 Northwards prograding fluvio-deltaic sandstones (shown blue) at the base of the Sherwood Sandstone Group interbedded with lacustrine fines shown clear (location map on next page). Major flooding surfaces (red) define prograding parasequence sets



Location map for East Irish Sea wells in Figure 8.1 on previous page

Above the highest of the claystone interbeds the Rottington Member at outcrop in west Cumbria comprises stacked fluvial channel fills and, in the absence of core data, is presumed to be the same where penetrated by wells offshore. From the evidence of the approximately 400m thick Rottington Member exposed around St Bees Head, with palaeoflow direction uniformly to the N and NW, it can also be assumed that by this time the fluvial system responsible was flowing all the way across the East Irish Sea Basin and on northwards into the Solway Basin. As there is no further indication that lacustrine environments were re-established it appears that the fluvial system was capable of supplying sufficient sediment to the basin such that it always kept pace with subsidence rates and maintained a through-flowing system.

In these outcrops the channel bases are commonly incised into previously deposited channel fills, each of which preserves a partial channel filling sequence of sandstones comprising a highly heterogeneous mix of bedforms representing all potential flow regimes as discussed in Section 3.2. This heterogeneity is amply illustrated by detailed examination of the Fleswick Bay outcrops, illustrated in Figure 8.2 where bedforms ranging from current ripples to high stage bars are all preserved within a series of channel-fills. Further examination of the west Cumbria outcrops, however, reveals that the larger scale arrangement and stacking of the fluvial channel fills is far from being random and that there are surfaces present which are laterally continuous (Figure 8.3). Each of these surfaces effectively forms a boundary between packages of fluvial channel fills that, despite the heterogeneity of the numerous individual channel fills forming the package, is itself of considerable lateral extent and, due to the low dips, can be traced along the

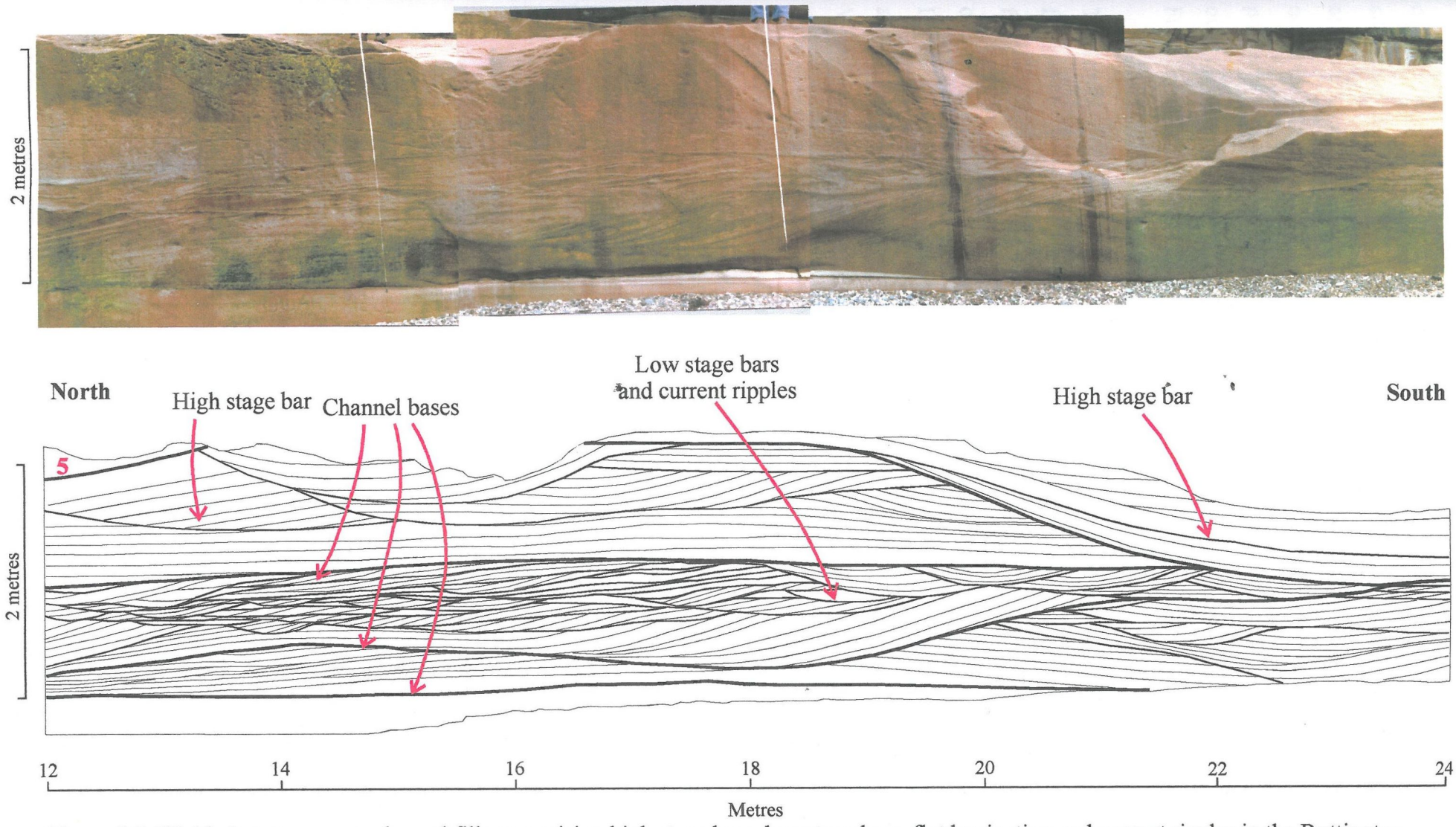


Figure 8.2 Highly heterogeneous channel fills comprising high stage bars, low stage bars, flat lamination and current ripples in the Rottington Member of the St Bees Sandstone Formation at Fleswick Bay, west Cumbria

outcrop for more than 1.5kms. Each of the surfaces appears to be compound in that they comprise the cumulative effect of numerous channel bases, each of which has cut to approximately the same level within the succession and therefore contributes to the overall near planar geometry of the surfaces (see discussion below in Section 9.5) and therefore probably equate with the equilibrium surfaces of Shanley and McCabe (1994). Although outcrop is often more limited, similar surfaces can be identified in the Chester Pebble Beds Formation at localities such as Bromborough Beach and Burton Point.

The stratal architecture of the Rottington Member, both in the interdigitation of lacustrine fines with fluvial sandstones and in the stacked fluvial channel sequences devoid of floodplain or sandflat sequences but subdivided by the laterally continuous surfaces, is clearly distinct from the overlying Calder Member and Ormskirk Sandstone Formation. Likewise, the Chester Pebble Beds Formation with its similarly stacked fluvial channel sequences comparable to the upper parts of the Rottington Member, is distinct from the Wilmslow and Helsby Sandstone Formation. These very different stratal geometries need to be explained in terms of a model of continental deposition that allows for variations in sediment supply, fluvial discharge and subsidence rates, each of which can have profound effects on the architecture of preserved sequences.

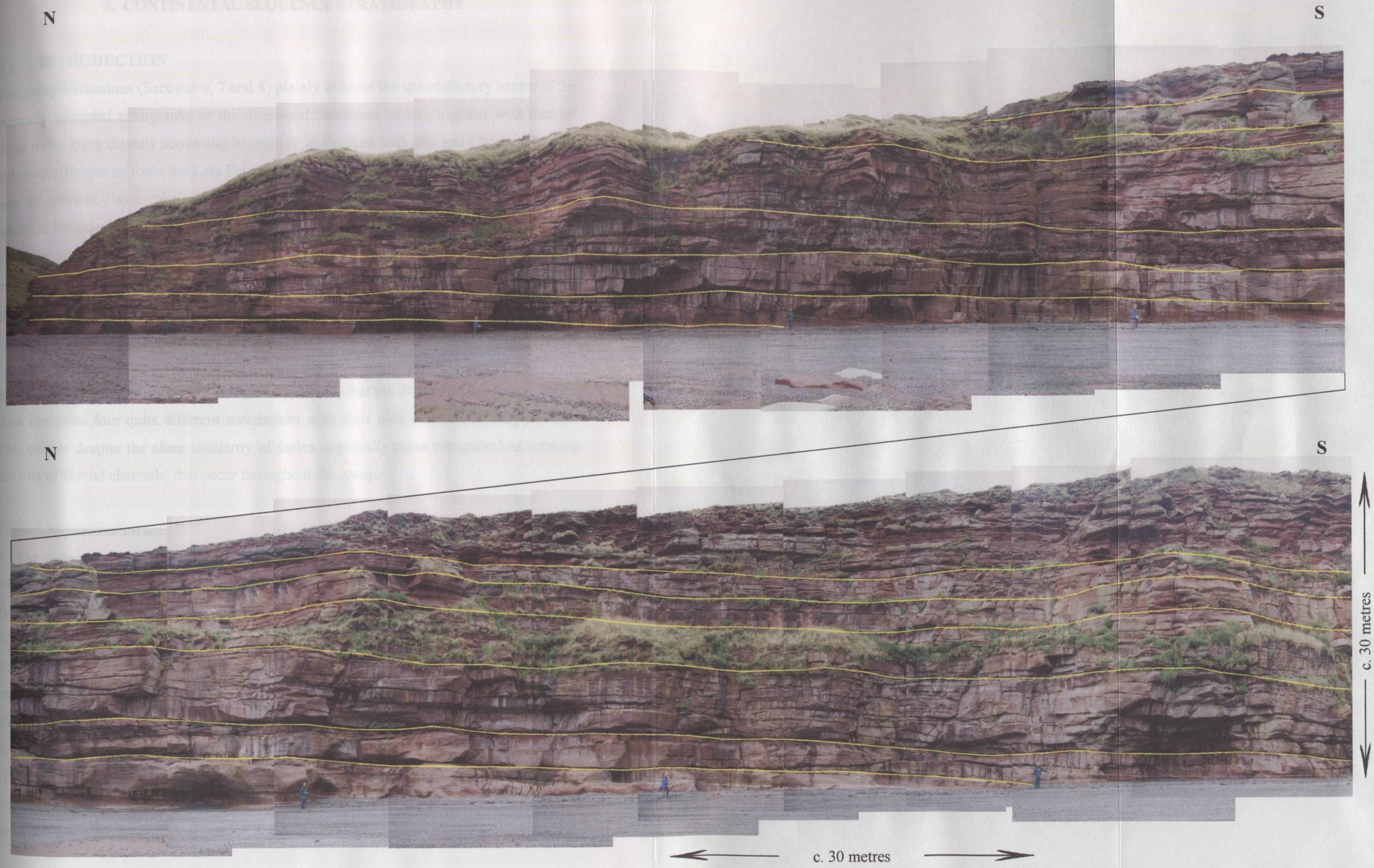


Figure 8.3 The Rottington Member of the St Bees Sandstone Formation exposed at Fleswick Bay, west Cumbria. The extensive coastal cliffs provide a unique opportunity in the Sherwood Sandstone Group to determine the stacking pattern of fluvial channel sandstone and the lateral continuity of the surfaces bounding sedimentary packages.

9. CONTINENTAL SEQUENCE STRATIGRAPHY

9.1 INTRODUCTION

Foregoing discussions (Sections 6, 7 and 8) plainly indicate the unsatisfactory nature of the currently accepted stratigraphy of the Sherwood Sandstone Group, together with that for those rocks lying directly above and beneath it, in the East Irish Sea and Cheshire Basins. Previous attempts to force the Late Permian to Early Triassic rocks of northwest England into the present 'layer-cake' lithostratigraphy have only served to confuse by erecting artificial boundaries and mis-correlating sedimentary facies, often over impossibly long distances without the benefit of either outcrop or well data. However, in dismissing the current scheme, it is clearly not sufficient to simply abolish the internal stratigraphy of the group entirely; an alternative is needed that better accommodates the architectural variety inherent in this eclectic mix of largely continental facies.

It has become apparent during the course of this study that the Sherwood Sandstone Group does comprise four quite different successions with their own distinct stacking patterns. This occurs despite the close similarity of facies, especially those recognised as forming the fills of fluvial channels, that occur throughout the group.

These four successions are:

A: The uppermost parts of the Sherwood Sandstone Group where it locally interdigitates with the overlying Mercia Mudstone Group, includes marine influenced clastic sabkha facies and also changes character significantly as it passes southwards from the East Irish Sea into the Cheshire Basin.

B: The whole of the upper and middle parts of the Sherwood Sandstone Group, including most of the current Ormskirk/Helsby and all the Calder/Wilmslow Sandstones, that are characterized by incised valley fills dominated by fluvial channel facies cut into heterogeneous successions of sandflat and playa facies.

C: The lower parts of the Sherwood Sandstone comprising the majority of the current Rottington Member and Chester Pebble Beds Formation successions where stacked amalgamated fluvial channel sequences dominate.

D: The basal parts of the Sherwood Sandstone where it interdigitates with the Barrowmouth Mudstone Formation, together with the Freshfield Sandstone and parts of the Kinnerton Sandstone Formation.

It is proposed to discuss the characteristics of each of these successions and attempt to erect a model that better explains their particular architecture and, possibly, might even predict the geometry and distribution of architectural elements within them. It is necessary first, however, to examine those models of continental sequence stratigraphy currently available in the public domain that may be able to assist in this process.

9.2 PREVIOUS MODELS

The application of sequence stratigraphic methods and terminology to continental successions began with the initial introduction of sequence stratigraphy as developed from seismic stratigraphy and used as a predictive tool in the hydrocarbon exploration industry. The definition of sequences controlled by eustasy within marginal marine settings necessarily requires a hinterland capable of supplying clastic sediment to the shoreline. Early sequence stratigraphic models incorporated fluvial systems that prograded during marine regression to build lowstand systems tracts comprising deltas and slope to basin floor fans, while the alluvial plain was subject to incision due to the lowering of base level. Subsequently, rising sea level flooded these sequences, initiating a retrogradational phase, thereby causing aggradation of fluvial deposits within the incised valleys and subsequently generating a maximum flooding surface across the previously exposed shelf and alluvial plain (e.g. Posamentier and Vail 1988; Van Wagoner *et al.* 1990). These models therefore depend on eustasy for their understanding of fluvial architecture and link this directly to this principal causative parameter.

These models therefore raise the question, highly relevant to the Sherwood Sandstone Group, as to how far from the coeval shoreline the effect of eustatic changes in sea-level may influence a fluvial system. The work of Fisk (1944) on the Mississippi was highly influential in indicating that this might be in excess of 1000 km upstream and has been quoted by numerous authors (e.g. Van Wagoner *et al.* 1990; Cant 1998). However, more recent work on the same river (Autin *et al.* 1991; Saucier 1994) as well as critical reviews of sequence stratigraphic models (e.g. Shanley and McCabe 1994; North 1996; Blum and

Törnqvist 2000) suggest that this is a significant over-estimate and that, depending on the time available, the effects of eustasy (in particular sea-level fall) may extend only a matter of 10's or at most a few 100 km inland.

The relevance to the Sherwood Sandstone Group is clear in that, with the exception of the very uppermost parts of the group (referred to as succession A above) there is good circumstantial evidence that any coeval shoreline is likely to be a considerable distance away from the East Irish Sea Basin and certainly from the Cheshire Basin (see Section 9.4 below). Not only could a shoreline be distant from the basins, it is also possible that there was a topographic elevation maintained between the Early Triassic basins such that any marine influence would have been even less likely. If this is the case then any applicable sequence stratigraphic model must be able to function independently of eustasy in seeking to explain the stratal architecture of the Sherwood Sandstone. A number of authors have attempted to erect sequence stratigraphic models for wholly continental successions and, in doing so, have generally turned for the main driving parameter to climatic variations (e.g. Antoine 1994; Bridgland 1994), to tectonic controls (e.g. Heller and Paola 1996; Currie 1997) or to a combination of the two (e.g. McKie and Garden 1996). It is noticeable that both the examples cited for purely climatically controlled sequence stratigraphic architecture relate to relatively recent (mainly Quaternary) successions, there being few specific examples in the literature from older strata. This may, in part, be a function of the inadequacy of the climatic record pre-Quaternary and reservations regarding the dating of wholly continental successions such that they can be tied to specific climatic variations.

Of particular note with respect to the Sherwood Sandstone Group (discussed further below) is the work of Miall and Arush (2001) with regard to implied tectonic controls on fluvial architecture and that of Demko *et al.* (2002) with regard to climatic controls. Miall and Arush (*op.cit.*) cite examples of thick stacked fluvial channel successions, remote from marine influences, within which sequence boundaries can only be recognised through the integration of a variety of techniques including facies logging, regional mapping, petrography and palaeocurrent analysis. These authors, in particular, stress the dangers of purely facies based analysis in such rocks, likening this to the 'pattern-matching' of simplistic well log correlation, a sentiment supported by the current investigation. In the examples they use, the Triassic Chinle Formation, the Jurassic Kayenta Formation and the

Cretaceous Castlegate Sandstone (all outcropping in Utah and Colarado), Miall and Arush (*op. cit.*) suggest regional tectonism, in part related to salt diapirism (Chinle and Kayenta) and in part to tectonic tilting (Castlegate) for the generation of regional sequence boundaries. Across these boundaries they record changes in detrital mineralogy reflecting source area modification, altered diagenesis resulting from prolonged exposure and shifts in palaeocurrent azimuth indicating changes in the regional palaeoslope. Most importantly, Miall and Arush (*op. cit.*) emphasise the presence of previously unrecognised, laterally extensive, surfaces that bound genetically related strata, the careful identification of which can significantly aid understanding of the regional tectonic history of an area. These authors do, however, point out that they have not taken climatic change into account, their only concern having been to elucidate the tectonic control on sequence architecture. The significant points raised by Miall and Arush (2001) have direct implications for large scale interpretations of the Sherwood Sandstone Group as well as possible implications for the more detailed interpretation of the fluvially dominated lower parts of the succession now referred to the Rottington Member and the Chester Pebble Beds Formation.

By contrast, Demko *et al.* (2002) using some examples from the same areas of Colorado and Utah, specifically but not exclusively the Upper Jurassic Salt Wash Member of the Morrison Formation, attempt to isolate the climatic controls on the architecture of fluvial systems. These authors discuss, in particular, the controls on aggradation and degradation in fluvial systems such as the Salt Wash Member which is wholly continental, being preserved within an intracratonic basin system that developed across the area following the final retreat of the Middle Jurassic sea (Robinson and McCabe 1998). Demko *et al.* (*op. cit.*) acknowledge the potential contribution of local tectonism in controlling base level but go on to consider the relationship between stream discharge and sediment flux under a range of climatic conditions. In effect these authors show that changing climate provides a means by which it is not only possible but highly likely that stream discharge and sediment flux remain out of phase with each other for substantial periods of depositional time. By invoking the work of Lane (1955) and Bull (1991) who demonstrate this relationship under static conditions (see Section 9.4), Demko *et al.* (*op. cit.*) develop conceptual models of stratal architecture for fluvially dominated successions. These models reveal a remarkable similarity to the upper parts of the Sherwood Sandstone Group (succession B above),

equivalent to the Calder/Wilmslow and the majority of the Ormskirk/Helsby Sandstones successions, and are discussed further below (Section 9.4).

It becomes clear that no single published model of continental sequence stratigraphy will adequately explain the variety of stratal architectures present within the Sherwood Sandstone Group. However, by continuing to break down the Sherwood into its four constituent successions as introduced in Section 9.1 it may be possible to define models that are most appropriate for each and, through this exercise, to better understand their relationship and those parameters that may have influenced the changes from one style to another.

9.3 UPPERMOST SHERWOOD SANDSTONE GROUP

Delineated as succession (A) in Section 9.1, this includes those uppermost parts of the Sherwood Sandstone Group that have been affected in their deposition and preservation by the marine transgression regionally responsible for the onset of Mercia Mudstone Group deposition. Marine influences have been recognised in the basal Mercia Mudstone from the geochemistry of the associated salts (Holser and Wilgus 1981) and sparse microfossils, mainly acritarchs (Warrington 1981). The transgression has been equated with the Röt transgression of northwest Europe and the southern North Sea (Jackson *et al.* 1995) although the correlation must be considered somewhat tenuous. It is, however, of note that the basal Mercia Mudstone Group is dated as latest Scythian/early Anisian (Warrington *et al.* 1980) and this coincides with a significant rise in sea level suggested by Haq *et al.* (1987).

Supporting evidence for marine influences also comes from the Sherwood Sandstone itself, as noted in Section 3.3.6, and the presence of primary anhydrites forming part of the clastic sabkha facies within well 110/8a-5 that have been tied to Early Triassic seawater chemistry (Greenwood and Habesch 1997). Seven such intervals are recorded within the core from this well (see Appendix II) and all occur in the uppermost Sherwood Sandstone Group succession and within 25m of the recognised contact between the Sherwood Sandstone and the overlying Mercia Mudstone. Interbedded facies include damp sandflats, sheetfloods and isolated fluvial channel fills, suggesting that the marine transgression was intermittent, flooding the area of well 110/8a-5 and regressing before again flooding back. In this

context, it is noticeable that the clastic sabkha intervals become progressively thicker upwards, consistent with an overall transgression.

Additional, but circumstantial, evidence for episodic transgression is provided by the presence of heavily bioturbated surfaces, including the ichnogenera *Skolithos*, in the core from well 110/14-3 (see Appendix II) and by the small outcrop at New Brighton (Section 3.3.6) with similar sedimentary characteristics to the clastic sabkha facies in well 110/8a-5. The bioturbated surfaces in well 110/14-3 appear to truncate aeolian dunes and sandsheets and all occur in the uppermost 30m of the Sherwood Sandstone. It is not, therefore, unreasonable to think that they may equate to the marine influenced facies in well 110/8a-5 although the stratigraphic framework proposed for the wells in Section 6.3 is not sufficiently definitive to establish a direct correlation between individual surfaces and clastic sabkha intervals. Further evidence for the nature of the transgression can be found in the Cheshire Basin where Mikkelsen and Floodpage (1997) have mapped from well and seismic data the presence of sandstone wedges that prograded towards the NW and are interdigitated with the basal Mercia Mudstone Group.

It seems highly likely that the succession comprising the uppermost parts of the Sherwood Sandstone Group and the associated basal parts of the Mercia Mudstone Group records a marine transgression that ultimately terminated Sherwood Sandstone deposition. This transgression probably invaded the East Irish Sea Basin from the W, conforming to inferred palaeo-slopes from well correlations in Section 6.4, and then flooded SE into the Cheshire Basin. The character of the transgression appears to conform to models proposed by Posamentier and Vail (1988), refined by Van Wagoner *et al.* (1990). These authors model the response to intermittently rising sea level as a retrogradational parasequence set in their Figure 10 (reproduced as Figure 9.1 herein).

According to this model each of the sedimentary packages of interbedded sandflat, sheetflood and fluvial channel facies bounded by clastic sabkha facies and by the bioturbated surfaces would conform to a parasequence and represent a lowstand systems tract within the overall transgressive sequence. The clastic sabkha intervals represent successive transgressive systems tracts and the bioturbated surfaces, bounding packages of aeolian dune and associated facies, are the landward representation of maximum flooding

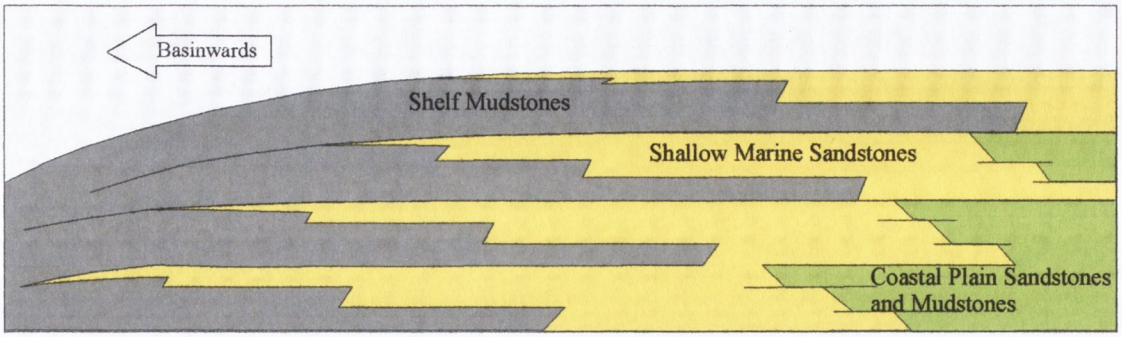


Figure 9.1 Schematic stratal architecture for retrogradational parasequences in a clastic dominated marginal marine setting (from Van Wagoner *et al.* 1990)

surfaces associated with these transgressions. Given that there may be seven or possibly more such parasequences present within the uppermost few 10's metres of the Sherwood Sandstone Group they are clearly thin but laterally extensive packages as would be suggested by the overall relief associated with the top Sherwood Sandstone diachroneity in Figure 6.5. Additionally, the clastic sabkha facies form within the sandflats exposed at the contemporaneous surface and it therefore becomes somewhat difficult to accurately define parasequence boundaries. In a basinwards direction the model would conventionally predict shelf mudstones as the lateral equivalent of each package. In the present case, as suggested in Section 6.4, it seems likely that the marine influenced Sherwood Sandstone packages can be correlated with mudstone/halite couplets in the basal succession of the Mercia Mudstone Group (Figure 9.2). If this is the case then it can be suggested that the clastic sabkha intervals probably equate to the mudstones, representing highstand conditions, while the intervening continental facies equate to the halites, representing lowstand conditions conducive to halite precipitation in basinward areas.

This uppermost part of the Sherwood Sandstone Group, together with lateral equivalents in the Mercia Mudstone Group, would appear to conform to conventional sequence stratigraphic models for an overall transgressive system.

9.4 UPPER SHERWOOD SANDSTONE GROUP

Delineated as succession (B) in Section 9.1 above, this forms the majority of the Sherwood Sandstone Group in most areas and can be in excess of 800 metres thick in the Cheshire Basin (well Knutsford-1) and 900 metres thick in the East Irish Sea Basin (well 113/26-1).

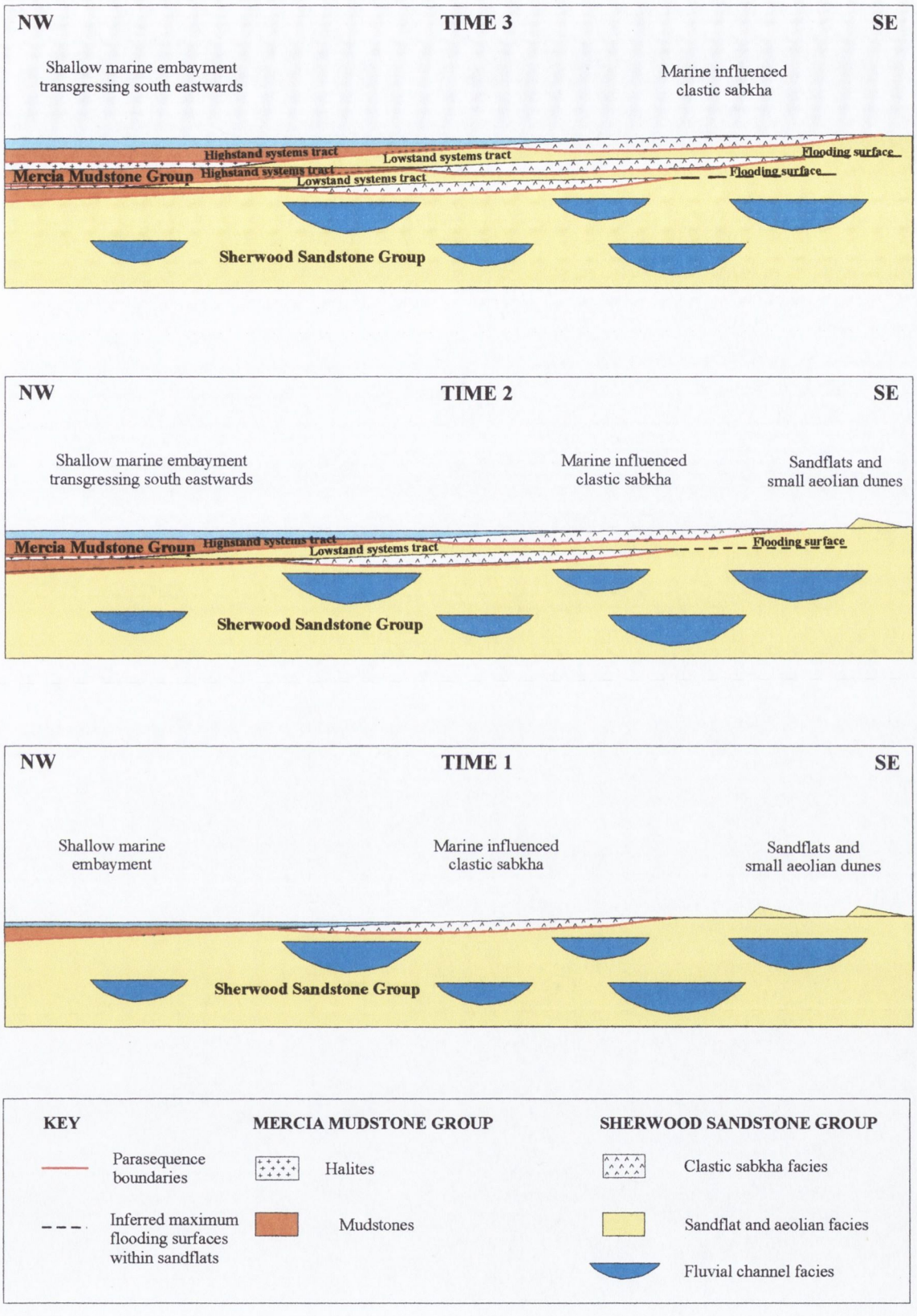


Figure 9.2 Schematic evolution of the stratal architecture in the southern East Irish Sea Basin for latest Sherwood Sandstone to earliest Mercia Mudstone depositional time and based upon successive marine highstands. The section illustrated extends from a near basin centre position on the left to a near basin margin position on the right and therefore conforms very approximately to the well section presented in Figure 6.5 (c. 25 kms.)

There are no indications of any marine influences recorded throughout the succession, either onshore in outcrops or in core from any wells. The location of any contemporary shoreline, if indeed there was one for much of Sherwood Sandstone depositional time, is not known but available published information (and unpublished data known to the author) would place it well beyond the limits of the East Irish Sea and Cheshire Basins and potentially much further afield for the majority of the succession under consideration. Reference to Warrington and Ivimey-Cook (1992) shows no record of marine facies during the Early to Mid Scythian within the limits of the British Isles and surrounding present-day continental shelf. The previously nearest recorded marine sequences of equivalent age occur either around the palaeo-Tethyan margin to the south, now exposed in parts of the Alpine Chain (e.g. Tollman and Kristan-Tollman 1985; Sauer *et al.* 1992), or associated with the Boreal Ocean in the present day Barents Sea area to the north (e.g. Wignall *et al.* 1998; Stemmerik *et al.* 1999). More recently published information, however, suggests that the southern extent of the Boreal Ocean may have been somewhat closer to the British Isles with marginal marine sequences having been identified among those previously thought to have been exclusively continental in East Greenland and in wells offshore central Norway (Seidler *et al.* 2004).

It is unclear from published data whether Early Triassic rivers to the west of Britain flowed ultimately northwards into the Boreal Ocean, as suggested by the regional palaeoslope, or turned southwards in the Kish Bank and Central Irish Sea Basins area to connect with the palaeo-Tethyan Ocean, as indicated by Audley–Charles (1970) and Warrington and Ivimey-Cook (1992). This latter supposition would run counter to the conclusions of Musgrove *et al.* (1995), based on well and seismic data, who map a thin Sherwood Sandstone Group succession comprising mainly basin margin facies across the Celtic Sea Basins. More general support for a northwards draining fluvial system during Sherwood Sandstone depositional time is also provided by Long *et al.* (2001) who propose SW to NE palaeoflow for Sherwood Sandstone rivers in the Slyne Basin west of Ireland from core and image log data in the Corrib Field and by Maddox *et al.* (1997) who record a Sherwood Sandstone Group succession in the North Channel Basin of near equal thickness to that in the East Irish Sea.

Regardless of which contemporary marine succession was closest to the British Isles, or into which the Early Triassic rivers may have flowed, for the majority of Sherwood Sandstone depositional time any fluvial system operating through the Cheshire and East Irish Sea Basins would need to exit those basins and still traverse a considerable number of other Early Triassic basins in order to reach the sea. This therefore implies that eustasy is unlikely to have been a significant factor in controlling stratal architecture prior to the advent of the first Mercia Mudstone marine transgression (?Röt) discussed above. It does, however, raise the question of how that marine transgression managed to arrive in the west of Britain basins, a question currently unanswerable through lack of information in critical areas such as the North Channel and Rathlin Basins (Figure 1.1), and, from whichever direction it was approaching, could it have influenced sequences towards the top of the upper Sherwood Sandstone Group succession being discussed in this section.

The gross architecture of fluvial channel and sandflat related facies in the upper Sherwood Sandstone Group, as determined in Section 6.4 (Figures 6.6 and 6.7), bears a more than passing resemblance to that predicted by Shanley and McCabe (1994). The presence of their incised basal surfaces, above which the valleys thus created are infilled by stacked amalgamated fluvial channel deposits, are related to changes in base level that are inferred to be eustatically controlled. Above these incised valley fills the succession comprises isolated fluvial channel sandstones enclosed within floodplain deposits representing reduced rates of base level rise balanced by sedimentation rates. Whether or not the upper parts of the Sherwood Sandstone successions are eustatically influenced, much of the succession under discussion was clearly not and a mechanism is therefore required that is capable of generating a similar architecture within a wholly continental environment.

Such a mechanism is provided by the work of Demko *et al.* (2002) who have modelled the effects of climatic change on patterns of fluvial discharge and sediment flux under a range of differing climatic regimes (discussed briefly above). In doing so these authors returned to the work of Lane (1955) as expounded by Bull (1991) in which net fluvial aggradation or degradation are related primarily to the relationship between bedload and stream discharge (Figure 9.3). Presuming a situation in which a river is initially in equilibrium (i.e. neither net deposition nor erosion), an increase in bedload and/or a decrease in stream discharge will initiate deposition and the river will aggrade its bed. Conversely, a decrease

in bedload and/or an increase in stream discharge will cause erosion, forcing the river to degrade its bed thereby incising into previously deposited sediments. In considering climatic change, Demko *et al.* (2002) looked at a range of climatic regimes from wet and tropical monsoonal climates through to dry seasonal and desert climates, the types of vegetation associated with these and the relative proportions of chemical and mechanical weathering. In doing so they concluded that the greatest equilibrium sediment flux is associated with wet and tropical monsoonal climates but that the vast majority of this comprises clay and silt grade material liberated through chemical weathering. With progressively drier climates the equilibrium sediment flux decreases but becomes increasingly dominated by sand and gravel grade material liberated by mechanical erosion.

The effects of changing climate are illustrated graphically in Figure 9.4 (from Demko *et al.* 2002) in which climate is presumed, for modelling purposes, to fluctuate on a temporal scale of 100 ka. This superficially nominal value is in fact close to the calculated eccentricity value for the earth's orbit which has been shown to have hardly varied over the

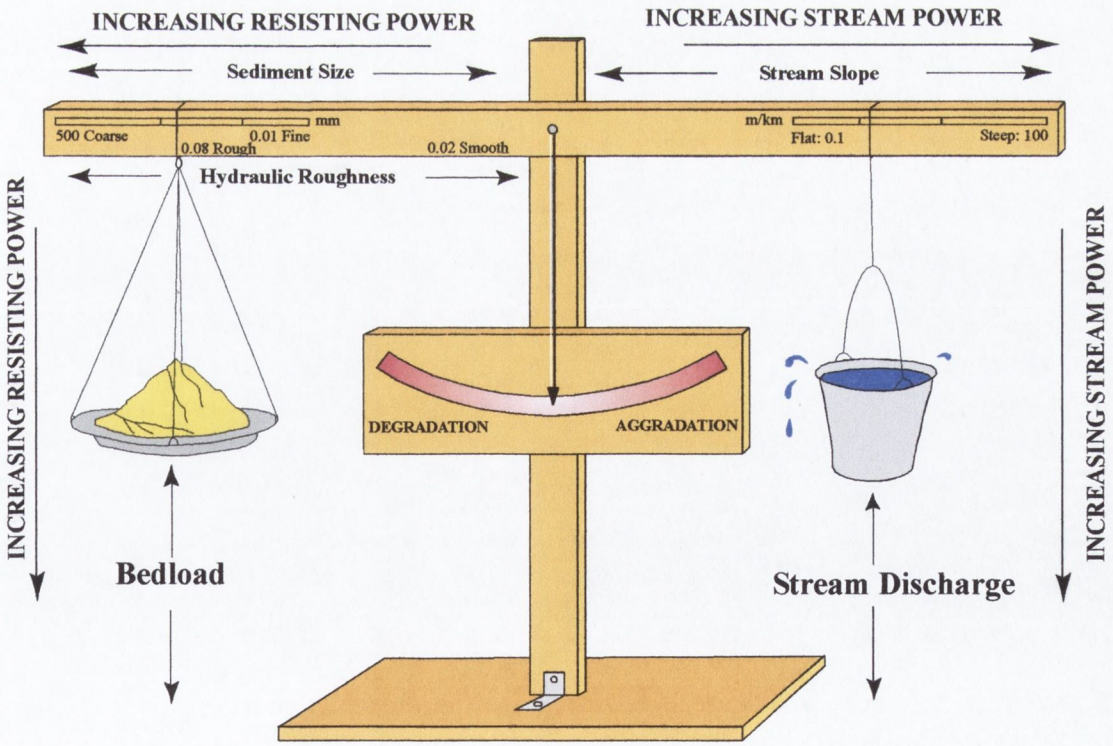


Figure 9.3 Theoretical relationship between stream discharge and bedload in a river (after Lane 1955 and Bull 1991).

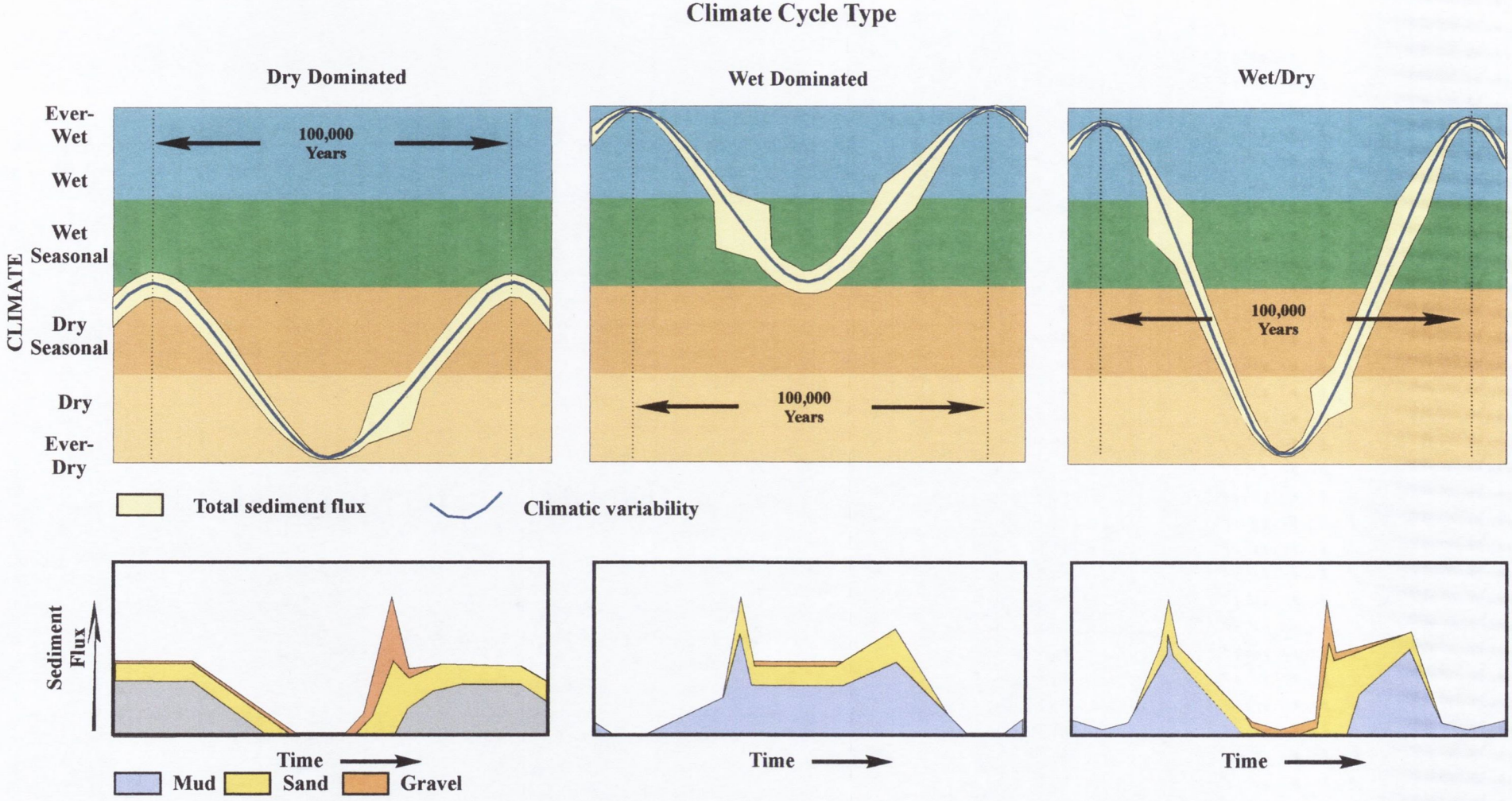


Figure 9.4 Theoretical relationship between climatically mediated stream discharge and sediment flux under a range of climatic regimes (from Demko *et al.* 2002)

last 500 Ma (Berger and Loutre 1994). Additionally, of the three major variables in the earth's orbit; eccentricity, obliquity and precession, the effects of the eccentricity have been most closely matched with climatic change (Blum and Törnqvist 2000) although the obliquity component, currently 41 ka. but likely to have been closer to 36 ka, during the Early Triassic (Berger and Loutre 1994), may also have been influential.

Within the range of climatic regimes shown it seems likely that the Early Triassic climate most closely resembles that depicted as being dry dominated although the sedimentological evidence in support of a perennial fluvial system would suggest that it was never entirely dry. The sediment flux, as shown in Figure 9.4, slowly decreases as the climate changes from being wet seasonal through dry seasonal into relatively dry but with an increasing proportion of this comprising sand grade material as mud becomes less plentiful. In the driest part of the climatic cycle the sediment flux decreases to a minimum in response to the paucity of discharge capable of transporting the bedload of the river. In effect the drainage basin enters a state of storage as sediment, dominated by sand and gravel, is still being generated through mainly mechanical weathering in the upper reaches of the river. A return to a wetter regime, and the corresponding increase in stream discharge, is suggested to release the stored sediment and generate a major pulse in the sediment flux that is out of phase with the climatic cycle. The sediment flux then returns to a state of near equilibrium with the discharge although, as the climate enters the most pluvial phase, the proportion of mud increases to a maximum, reflecting the greater effect of chemical weathering under these conditions.

The climate change model therefore provides a means by which the maximum sediment flux and the maximum stream discharge are not coincident. Rather, there are episodes during which the sediment flux increases dramatically, generating conditions favourable for rapid net deposition and aggradation, and episodes during which discharge increases without a concomitant increase in bedload. At such times the river would be likely to undergo net degradation, reworking previously deposited sediment and incising its floodplain. Demko *et al.* (*op. cit.*) proposed a idealised stratal architecture that resulted from this imbalance, reproduced here as Figure 9.5, that illustrates the effect of alternating phases dominated by degradation and then aggradation. Interestingly, this also generates incised valley systems filled with stacked amalgamated fluvial channel deposits overlain

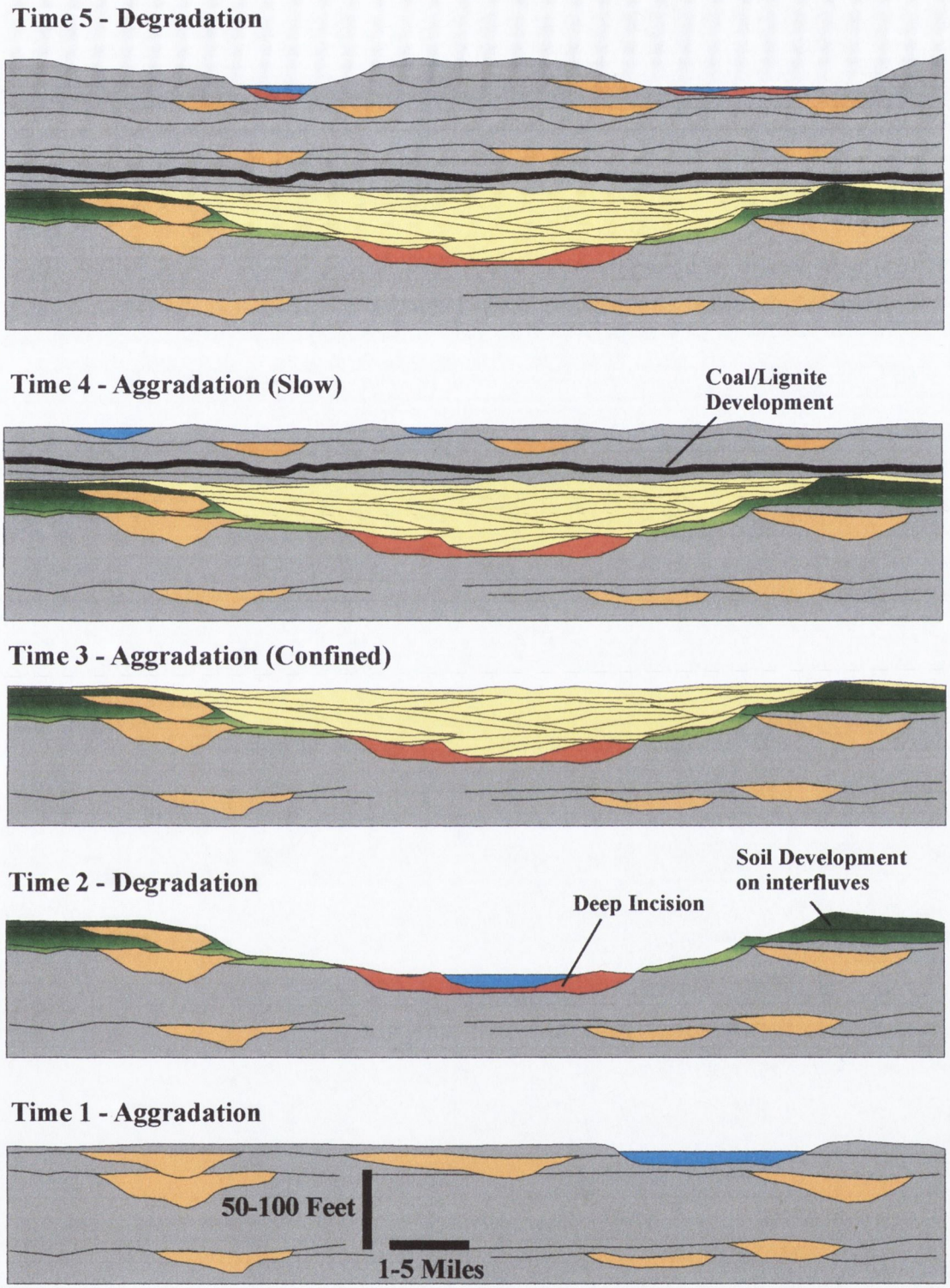


Figure 9.5 Staged development of stratal architecture based upon climatically mediated alternating episodes of fluvial aggradation and degradation with cycles recorded by distinct facies associations that are bounded by chronostratigraphy significant surfaces (from Demko *et al.* 2002)

by isolated fluvial channel sandstones enclosed within floodplain deposits. In this case it can be inferred that incision occurs during the most pluvial part of the climatic cycle; that sediment flux and discharge become effectively balanced as the climate becomes drier and, presumably, during this phase the river remains trapped within the previously incised valley system. As the climate begins to become wetter and stream discharge increases the sediment pulse is released, the river aggrades rapidly, infilling the incised valley until it breaks out onto the wider floodplain. At this stage, both the increased area of the floodplain and the declining sediment flux, especially the coarser grained bedload component, increase the preservation potential of floodplain facies (sandflats etc. in the case of the Sherwood Sandstone) and therefore render it more likely to generate isolated channels encased within those deposits.

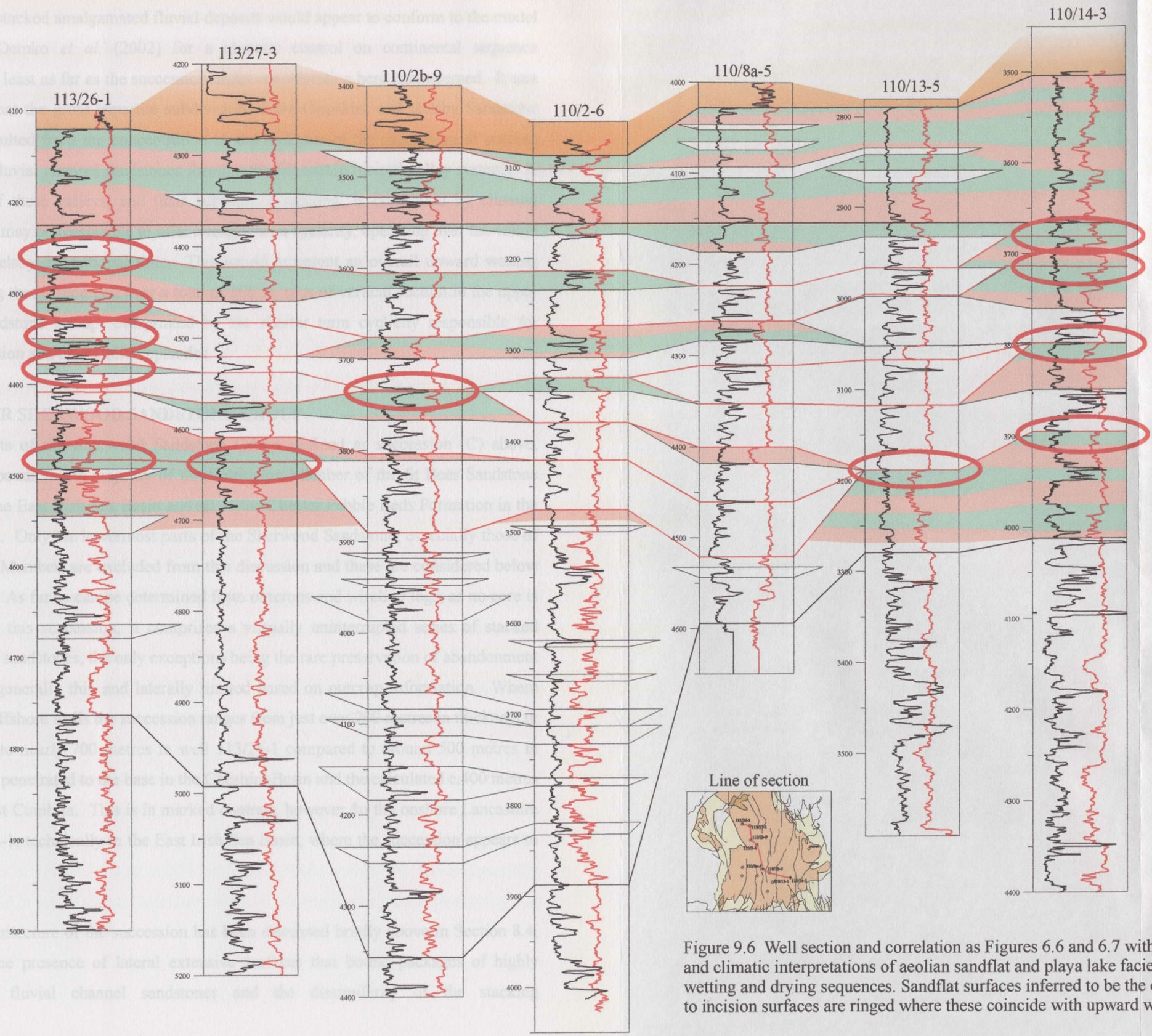
Notwithstanding the discussions above regarding the extent to which eustatically controlled changes in base level may have influenced the generation of the stratal geometries delineated in the upper parts of the Sherwood Sandstone Group, it is apparent that similar architectures can be generated under wholly continental conditions. In the absence of definitive marine deposits it therefore seems somewhat presumptuous to invoke a eustatic control on base level in successions where none is apparently necessary. Whether this applies in total to the Sherwood Sandstone succession delineated as (B) herein is clearly open to some doubt, following the discussions above and reservations regarding the precise location of a contemporary shoreline. However, until such time as that question can be resolved, and with no hint of a marine influence in the Sherwood Sandstone below the lowest clastic sabkha sequence in well 110/8a-5, it is consistent with the available evidence to regard the repeated episodes of alternating incision and aggradation as wholly continental in character and most likely to have been climatically generated.

Fortunately this hypothesis can, to some extent, be tested in the Sherwood Sandstone Group succession as a consequence of the climatic record preserved within the sandflat and associated facies (see Section 3.6). The upward drying and upward wetting sequences recorded in the transitions between playa lake, sandflat and aeolian facies have been readily identified in outcrop (Figure 3.42) and in cored intervals (Figure 3.43) but can also be identified in uncored well sections by careful examination of the wireline logs,

especially sonic velocities and, where available, density logs, both of which respond to preserved porosity (see comments in Sections 2.3, 3.6 and 4.3). For reasons associated with both depositional porosity, including clay content, and diagenesis the aeolian sequences preserve very high porosities and these generally become progressively less through dry and damp sandflat facies into wet sandflat and playa lake associated facies that preserve the lowest porosities. Therefore, where upward decreases in sonic velocity and decreases in gamma response correspond through a sandflat succession it is highly likely to represent an upward drying profile. Conversely, an upward increase in sonic velocity and gamma can be interpreted as a wetting profile.

Using both core derived facies and the wireline characteristics from the non-fluvial successions across a selection of suitable wells taken from the well sections in Figure 6.6 and 6.7, the climatic signal can be determined across a significant area of the East Irish Sea Basin (Figure 9.6). If it is assumed, not unreasonably, that the climatic changes occurred basin-wide then transitions can be correlated between wells as shown and these probably represent the nearest approach to time lines that can be determined in a biostratigraphically barren succession. Clearly the individual facies types do not correspond across the basin; an upward drying sequence in well 110/14-3 near the basin margin may be represented by a transition from damp sandflat facies to aeolian dunes, while the same transition in a near basin centre well such as 110/2b-9 is likely to be represented by playa lake or playa margin facies overlain by wet and damp sandflat facies.

From the suggested correlations of both the fluvial channel sequences and the interpreted climatic signals as shown in Figure 9.6 it is apparent, as suggested in Section 6.4, that if the climatic correlations approach time lines then the major basal surfaces to the stacked fluvial channel sequences deeply incise into previously deposited rocks. Where it is possible to trace these incision surfaces laterally into adjacent sandflats (highlighted in red in Figure 9.6) they invariably correlate, as near as can be determined, with an upward wetting sequence. The implication of this correspondence is that it appears highly likely the fluvial incision occurred during a period of time when the climate was relatively wet and, referring back to the suggestions of Demko *et al.* (2002), there was an excess of stream discharge over sediment flux. The relationship between the climatic signal as recorded in sandflat and related facies and the fluvial incision and aggradation responsible



Sandlfat surfaces inferred to represent the correlative conformity to fluvial incision surfaces

Sequence exhibiting overall upward drying defined either by the vertical association of core derived facies or by progressive changes in wireline character that have been correlated to such associations within cored intervals

Sequence exhibiting overall upward wetting defined either by the vertical association of core derived facies or by progressive changes in wireline character that have been correlated to such associations within cored intervals

Figure 9.6 Well section and correlation as Figures 6.6 and 6.7 with fluvial channels blanked and climatic interpretations of aeolian sandflat and playa lake facies added to show upward wetting and drying sequences. Sandflat surfaces inferred to be the correlative conformities to incision surfaces are ringed where these coincide with upward wetting sequences.

for preserving stacked amalgamated fluvial deposits would appear to conform to the model proposed by Demko *et al.* (2002) for a climatic control on continental sequence stratigraphy, at least as far as the succession under consideration here is concerned. It was noted earlier that the gross tripartite subdivision of the Ormskirk and Helsby Sandstone Formations resulted from the concentration in the mid part of the succession of stacked amalgamated fluvial channel sandstones forming the fill within incised valley systems. If the incision of these valleys, and their subsequent infilling, is controlled by climatic change, then it may be reasonable to infer a longer term cyclicity, operating over the whole of Ormskirk/Helsby depositional time. This would represent an overall upward wetting and then drying that is recorded over a total of 200 m. plus of vertical section in the upper Sherwood Sandstone Group, overprinted by the shorter term cyclicity responsible for individual incision and aggradation episodes.

9.5 LOWER SHERWOOD SANDSTONE GROUP

The lower parts of the Sherwood Sandstone Group, defined as succession (C) above, broadly corresponds to the majority of the Rottington Member of the St Bees Sandstone Formation in the East Irish Sea Basin and all of the Chester Pebble Beds Formation in the Cheshire Basin. Only the lowermost parts of the Sherwood Sandstone, especially those of the Rottington Member, are excluded from this discussion and these are considered below in Section 9.6. As far as can be determined from outcrops and wireline logs, as no core is available from this succession, it comprises a virtually uninterrupted series of stacked fluvial channel sandstones, the only exceptions being the rare preservation of abandonment fines that are generally thin and laterally limited based on outcrop information. Where penetrated in offshore wells the succession ranges from just over 200 metres in thickness in well 110/20-1 to nearly 700 metres in well 113/26-1 compared to around 500 metres in both wells that penetrated to the base in the Cheshire Basin and the calculated c.400 metres exposed in west Cumbria. This is in marked contrast, however, to the onshore Lancashire well Thistleton-1, technically in the East Irish Sea Basin, where the succession appears to be absent.

The stratal architecture of the succession has been discussed briefly above in Section 8.4, in particular the presence of lateral extensive surfaces that bound packages of highly heterogeneous fluvial channel sandstones and the dissimilarity of the stacking

characteristics of this succession to those above. The absence of any sequences representing floodplain deposition is particularly notable and implies either that none were present, i.e. that the active fluvial system filled the entire width and length of the available basinal area at the time, or that any contemporaneous floodplain deposits were reworked during migration or avulsion of the river and hence were not preserved. There is nothing in the sedimentary characteristics of the succession, as seen and logged in west Cumbria and in the Cheshire Basin, that would suggest the fluvial system responsible was significantly different to that recorded in the stratigraphically overlying succession discussed above. It seems logical therefore to consider whatever evidence is available regarding the structural basin geometry at this early stage in Sherwood Sandstone depositional time.

The apparent absence of the Rottington Member from the Thistleton-1 well in west Lancashire where, admittedly from wireline characteristics alone, it seems that sequences attributable to the overlying Calder Member rest directly upon a thin Cumbrian Coast Group (Appendix I) may shed some light on the nature of the early Sherwood Sandstone basins. Likewise, the very thin Rottington Member recorded in well 110/20-1 near the present-day margin of the basin and the absence of any equivalent succession in the southern parts of the Cheshire Basin. It has been noted previously that the Permian basins of NW England form a precursor, but much more areally restricted, structural system to the later Triassic basins (e.g. Tonks *et al.* 1931; Earp and Taylor 1986), while Quirk and Kimbell (1997) suggest an Early Permian rifting episode as being responsible for the creation of post-Variscan graben and half-graben within which the Collyhurst Sandstone accumulated. There is therefore a reasonable array of evidence that the precursor Permian basins at least were more areally restricted, potentially linear, structures probably aligned sub-parallel to the dominant fault trends with a mainly N-S component. Early Triassic extension undoubtedly resulted in these basins becoming larger, particularly with respect to their capacity to accommodate Sherwood Sandstone deposition but it is also likely that they did not reach their full extent until Mercia Mudstone depositional time and possibly not until the Mid to Late Triassic, consistent with subsidence curves plotted by Rowley and White (1998).

On this basis it is possible to suggest that the Permo-Triassic basins developed from restricted graben and half-graben initiated during Early Permian rifting and became progressively larger through time, both with respect to the thickness of accumulated sediment and also with respect to their areal extent, subsequent sedimentary sequences being likely to overstep earlier sequences as the basinal system developed. This therefore implies that the structural basin system in which the Rottington Member and the Chester Pebble Beds Formation were deposited was smaller, potentially narrower and more linear in geometry, than that available for subsequent deposition. Given both that the fluvial system operating during lower Sherwood Sandstone depositional time was essentially the same as that later on, and that the basin geometry was sufficiently developed to allow a through-going river with a significant hinterland, it is possible that the early Sherwood Sandstone river was capable of combing the entirety of its floodplain. Rowley and White (1998) also comment that active rifting in the East Irish Sea area lasted into the Early Triassic, contrary to Quirk and Kimbell (1997) who suggest that rifting was a Permian event. If the former are correct then active faulting is likely to have been at least partially coeval with deposition of the Rottington and Chester Pebble Beds successions.

This supposition accords with calculations based on seismic data of Early Triassic syn-depositional fault movement on the Keys and Formby Point Faults by Jackson and Mulholland (1993). These authors show approximately 700m of displacement on both faults during Sherwood Sandstone Group depositional time, of which nearly 600m is suggested to have occurred during deposition of the St Bees Sandstone Formation.

If the proposed basin geometry and timing of fault movements are valid then the stratal architecture of the succession under discussion becomes easier to interpret. Figure 9.7 shows schematically the potential development of this architecture in an episodically fault controlled laterally restricted basin. At times when there was little or no net subsidence (Time 1) the river would be likely to comb the full width of the basin but, in doing so, would be restricted by a range of parameters as to the depth to which it could entrench its bed. These parameters include the water table, the basin geometry and, given the supposition of a through-going fluvial system, the elevation of both the input and output points to the basinal system. At any given time and place these parameters combine to describe a surface below which the river is incapable of entrenching and hence, in

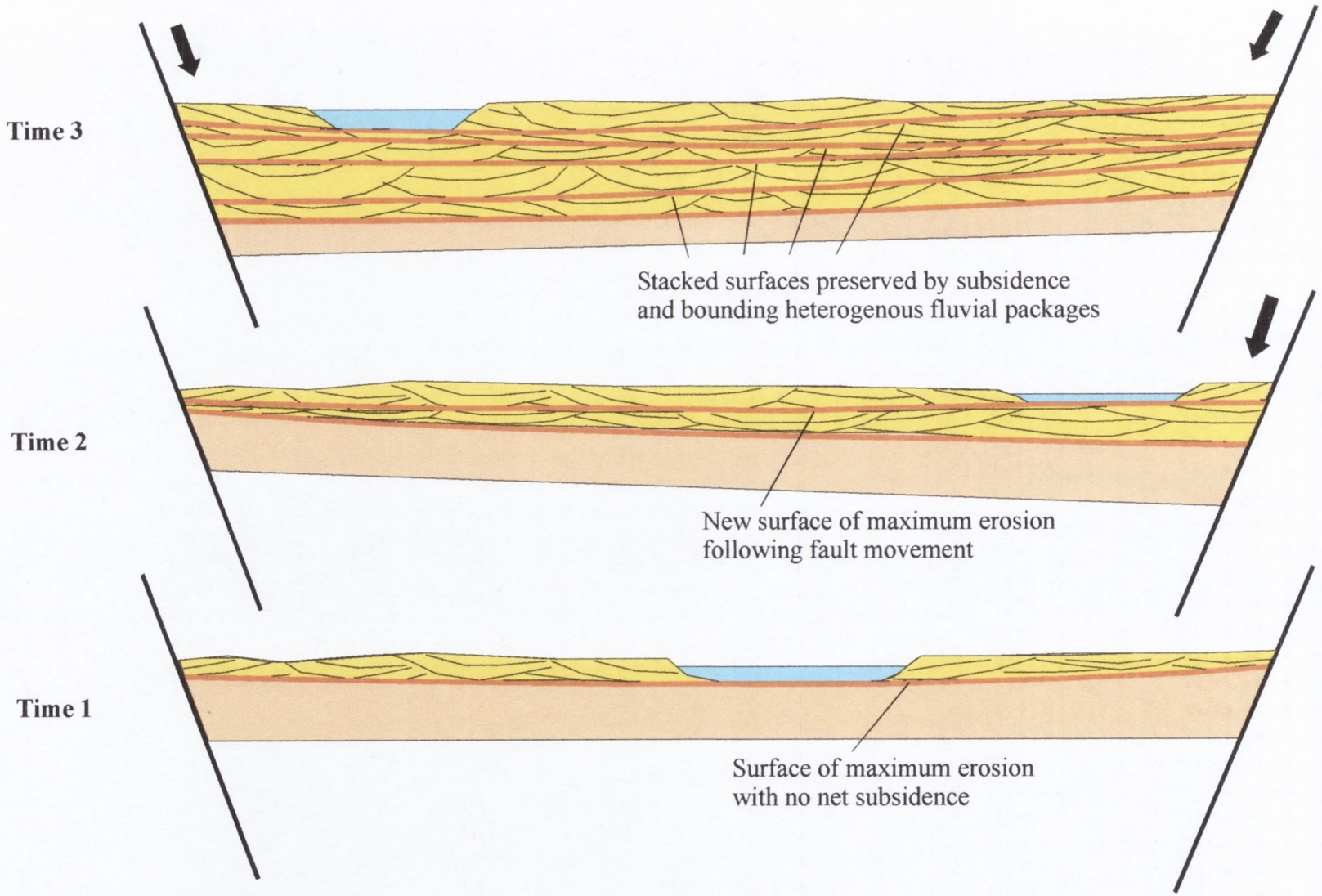


Figure 9.7 Schematic representation of fluvial deposition within a restricted basin system and the generation of laterally continuous bounding surfaces related to successive episodes of fault induced subsidence

migrating or at times catastrophically avulsing across the floodplain, the channel base will cumulatively generate that surface. Because of the various interacting parameters that influence the surface it is unlikely to be planar but will still form a continuous surface that can be theoretically traced throughout the basin.

Should one of the marginal faults activate and effectively generate additional accommodation space (Time 2) then the river must immediately adapt to a new set of parameters and a new surface which must of necessity be some distance above the old surface. The separation of the new and old surfaces will have been dictated, to a considerable extent, by the amount of movement on the marginal fault and by any change in the basin geometry that this has caused. The creation of a new surface, progressively generated as the river continues to scour its floodplain, will preserve a package of sediment that comprises all the previously abandoned channel fills, with all their internal heterogeneity resulting from the vagaries of the successive floods, scour and fill events and abandonments since the creation of the old surface. It is clear that the sediment supply and the stream discharge throughout this process must have been sufficient to enable the river to always keep pace with subsidence and maintain its through-going flow such that the basin system is effectively over-filled at all times. If this were not the case then a rapid fault induced subsidence event would have created a lake within the basin, even if only temporarily, but there is no evidence in the sedimentological record that this occurred post the events that produced the basal Sherwood Sandstone discussed in Section 9.6 below.

Continued fault induced subsidence (Time 3) would have generated successive surfaces, potentially on both margins in this simplistic representation (nominally the Keys and Formby Point Faults as discussed above), but in reality movement is likely to have occurred on various faults giving a much more complicated geometry. The net result, however, will still have been the preservation of successive stacked packages of fluvial channel fills, internally heterogeneous but bounded by surfaces that could potentially be preserved basin wide. The scale of the packages in west Cumbria where they are observable over a distance compatible with realizing their lateral extent varies from less than two metres to around five metres in thickness. Similar preserved thicknesses can be seen at Bromborough Beach and Burton Point although these localities do not permit the lateral continuity to be assessed. These thickness values therefore set constraints on the

amount of fault displacement occurring during any one episode of fault activity. The fact that floodplain fines are not preserved within the available and visible sections presumably reflects a combination of minimum channel depth compared to fault displacement and the activity of the fluvial system in combing that floodplain and reworking any fines that might otherwise have been preserved.

It is difficult to categorize the surfaces defined and described in this succession with any published sequence stratigraphic nomenclature. The surfaces clearly bound a conformable succession of genetically related strata but do not qualify as either unconformities or flooding surfaces. Indeed the term flooding surface has little meaning and no application to the succession under consideration. Within the terminology proposed by Van Wagoner *et al.* (1990) the closest definition is that for a bedset which these authors propose comprises 'a relatively conformable succession of genetically related beds bounded by surfaces of erosion or non-deposition.' However, the hierarchy of stratal units defined by Van Wagoner *et al.* (1990) demands that bedsets be component parts within a parasequence which is then bounded by marine flooding surfaces or their correlative surfaces. Clearly this latter stipulation does not apply and, in any case, the term bedset is intended to be of limited lateral extent whereas the surfaces in the Sherwood Sandstone must by their nature be basin wide.

The identification of cryptic sequence boundaries within fluvial successions by Miall and Arush (2001), although not quite used in the same sense as here, probably equates better with the concepts proposed. The surfaces described by these authors are discriminated by various changes that occur across them including the detrital composition of the sandstones, shifts in palaeocurrent trends and evidence of early diagenesis. Although the latter has not been observed in the Sherwood Sandstone the former certainly have and, in practice, the dramatic changes in apparent palaeoflow direction between bedforms directly above and below the surfaces provide the most obvious means of identifying the surfaces in outcrop. It is also easy to imagine the amount of time potentially condensed into a single surface as the fluvial system repeatedly combs the width of the basin between episodic fault movements. Any change in the detrital composition of the sandstones resulting from source area evolution or changes in the hinterland would be most clearly defined across such surfaces. These observations, however, serve only to aid identification

of the bounding surfaces whereas the surfaces themselves are suggested to be a direct result of the tectonic control on the creation of accommodation space in an areally restricted basin system.

It is interesting to note that surfaces similar in character to those described here are observable within the stacked amalgamated fluvial channel sandstones of the overlying succession (B). The generation of these must be somewhat dissimilar as the river in these cases is aggrading and infilling a previously incised valley system that was not fault controlled when the surfaces were being created. However, there is some similarity in that both rivers are infilling a laterally constrained accommodation space, the narrow basin in one instance and the incised valley in the other. It may be that the method of valley filling, and the lateral constraints on channel migration imposed by the valley geometry, generates a similar stratal architecture. If, for example, shorter term climatic changes than those responsible for the incised valley operated during the filling stage, then it becomes possible to imagine a pulsed fill within the valley separated by episodes of relative quiescence and the generation of similar surfaces but on a smaller scale.

9.6 BASAL SHERWOOD SANDSTONE GROUP

The architecture of the basal succession of the Sherwood Sandstone Group in the East Irish Sea Basin, termed succession (D) above in Section 9.1, has been described in some detail in Section 8.3. In consideration of the discussions regarding the interdigitation of the basal Sherwood Sandstone Group with the Barrowmouth Mudstone Formation in the northern East Irish Sea Basin, the succession discussed here includes both of these despite their currently being regarded as Triassic and Permian respectively. Additionally, some consideration must be given to the nature of the contact between the Sherwood Sandstone and those rocks directly underlying it in the southern East Irish Sea and Cheshire Basins. Where penetrated the combined basal Sherwood Sandstone and Barrowmouth Mudstone succession is approximately 200 metres thick although the top can be extremely difficult to define for the reasons stated previously.

Where the Sherwood Sandstone Group overlies sandstones of the Freshfield Sandstone Member or the Kinnerton Sandstone Formation (Figure 1.2) the contact appears to be extremely sharp (wells 110/20-1 and Knutsford-1; Appendix I) and is probably analogous

to that logged at Burton Point (59.00 m on Burton Point log in Appendix II). This contact is almost certainly erosive although the outcrop is not sufficiently extensive for this to be definitive. Wherever exposed, sandstones of the Kinnerton Sandstone Formation comprise aeolian dunes and sandsheets with minor, potentially ephemeral, fluvial channel fills (the Freshfield Sandstone in nowhere exposed and, to the authors knowledge, has not been cored in any offshore well. It seems likely therefore that this basal surface to the Sherwood Sandstone, throughout the northern parts of the Cheshire Basin and into the southern parts of the East Irish Sea Basin, marks the advent of the fluvial system that will subsequently dominate Sherwood Sandstone deposition. As such it can be regarded as a sequence boundary and is potentially unconformable through these areas although there is insufficient evidence to demonstrate this categorically. It is possible that the basal surface forms part of an incised valley system cut through the previously deposited mainly aeolian sandstones but this also remains supposition.

Given interpretations cited above of the Barrowmouth Mudstone in the central and northern parts of the East Irish Sea Basin as representing mainly lacustrine fines, into which the fluvial sandstones of the Sherwood Sandstone prograded (Sections 3.4.1 and 8.4) there therefore must be a surface within this succession that is the conformable correlative of the basal erosion surface to the south. Defining this in practice in the southern East Irish Sea Basin is complicated by the fact that part at least of the Barrowmouth Mudstone succession in this area must be the lateral equivalent of the Late Permian marine rocks of the St Bees Evaporites which interdigitate with the claystones and thin southwards. In the southern parts of the East Irish Sea Basin this is clearly the case where sandstones of the Freshfield Sandstone overlie a thin Barrowmouth Mudstone but are themselves overlain by the basal surface of the Sherwood Sandstone Group.

Further north the St Bees Evaporites are clearly present in all wells that penetrated to this depth and, as depicted in Figure 8.1, the distal equivalents of the Sherwood Sandstone fluvial channel sandstones are suggested in places to rest directly on the evaporites. In these areas the top of the evaporites, and therefore the base of the Barrowmouth Mudstone Formation, becomes the conformable correlative of the basal Sherwood Sandstone erosion surface in the southern parts of the basin. The stratal architecture is then more readily defined and can be interpreted in terms of a prograding clastic system into a standing water

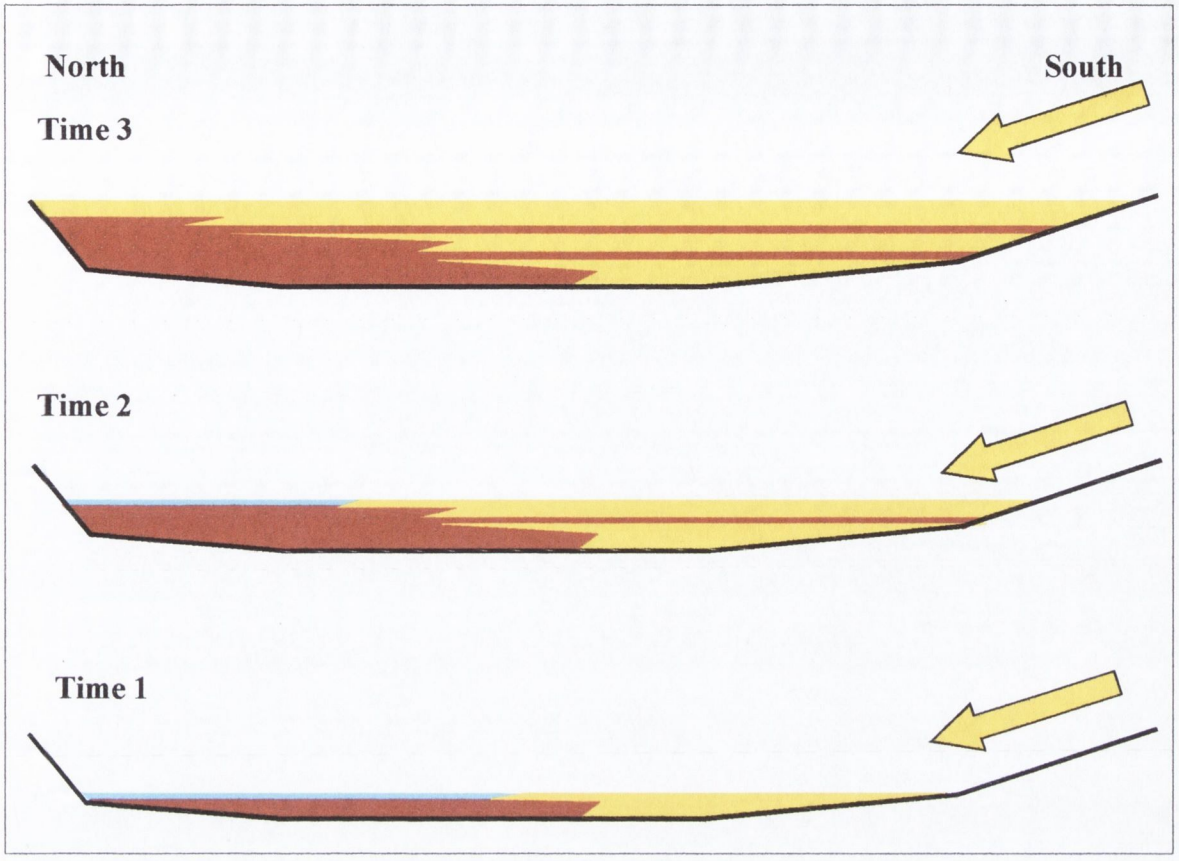


Figure 9.8 Schematic representation of lacustrine fluvio-deltaic deposition in an under-filled basin with successive episodes of delta progradation and flooding controlled by the climate

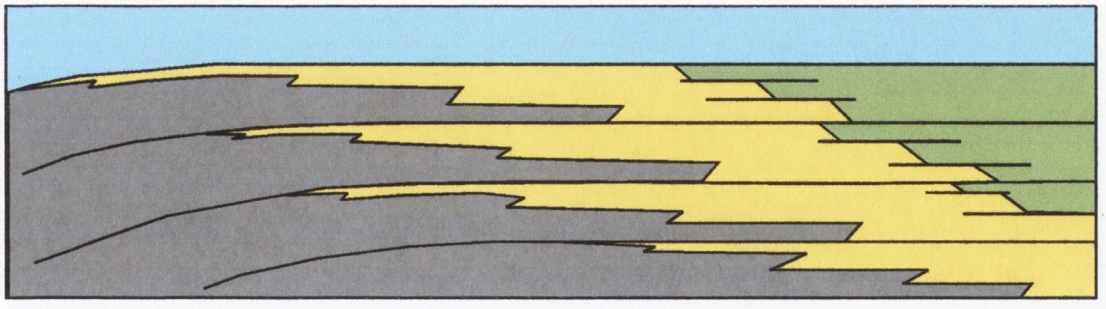


Figure 9.9 Schematic stratal architecture for progradational parasequences in a clastic dominated marginal setting (from Van Wagoner *et al.*1990)

body. This is schematically represented in Figure 9.8 which shows three illustrative time periods representing lacustrine lowstands and hence episodes of maximum fluvio-deltaic progradation.

The geometry of the sandbodies generated and their relationship with the lacustrine fines bears a close similarity to that predicted for progradational parasequences in a marginal marine setting as shown in Figure 9.9 (from Van Wagoner *et al.* 1990). It therefore seems feasible to assume that the architectural elements present in the classic sequence stratigraphic model will also be present in the lacustrine version even if the sedimentary facies differ. Reference to Figure 8.1 would appear to justify this conclusion as flooding surfaces together with highstand systems tracts, represented by the extensive mudstone intervals, and lowstand systems tracts represented by the fluvio-deltaic sandstones and their correlative lacustrine fines can all be identified.

In considering the relationship between the lacustrine fines and the prograding fluvio-deltaic clastics fed by the Sherwood Sandstone river (or rivers) it is, however, necessary to reflect that the northern East Irish Sea Basin would in all probability have been an area of internal drainage at the time. The stream discharge and the sediment flux entering this area of the basin would have been climatically controlled in the same way as that discussed for the upper parts of the Sherwood Sandstone above but, additionally, lake levels would also have been controlled by climate. There is therefore a negative feedback between the fluvial and the lacustrine systems in that any increase in stream discharge, thereby increasing the transporting capacity of the river and hence the sediment flux, will also raise the lake level and render it more difficult for the lacustrine delta to prograde. It would then appear necessary for there to have been some additional sediment input, or extraordinary sediment flux, to enable the river to overcome rising lake levels and transport clastic material considerable distances northwards. The climatically mediated model of Demko *et al.* (2002), discussed above in Section 9.4, provides such a mechanism. The effect of a rapid increase in sediment flux attendant on an increasing discharge as the climate became wetter and following storage during a relatively dry episode would both generate aggradation in the upstream reaches and progradation in the downstream lacustrine deltas.

The stratal architecture of this lowermost part of the Sherwood Sandstone, and other associated formations, does bear comparison with predicted sandbody geometries for a marginal marine prograding system. However, unlike the classic sequence stratigraphic model of Van Wagoner *et al.* (1990) where eustasy is the major controlling parameter, in the present instance the major control on base level and hence the architecture is again the climate. The significant difference between this basal succession and that higher up in the Sherwood Sandstone, however, is the absence of a through going fluvial system such that the early Sherwood Sandstone East Irish Sea Basin can be regarded as essentially under-filled.

9.7 CONTROLS ON CONTINENTAL SEQUENCE STRATIGRAPHY

From the foregoing interpretations of stratal architecture throughout the Sherwood Sandstone Group and the attempts to rationalize these in terms of published models of continental sequence stratigraphy it has become apparent that no single model currently available is capable of explaining the variety of geometries present. This inability would seem to stem from the preference of authors to stress one particular controlling parameter to the near exclusion of all others in an attempt to present a relatively simplified and comprehensible model. While this aim may be laudable in itself the result can easily become an over-simplification that does not serve the fundamental objectives of anyone seeking to predict stratal architecture and sandbody geometries. Numerous examples could be cited but three in particular serve to illustrate this point.

Demko *et al.* (2002) have been extensively cited in this discussion and their model of climatically mediated fluvial degradation and aggradation clearly has considerable application to the Sherwood Sandstone Group. In their abstract and presentation, however, there is little mention of the role played by tectonics and the effect that changing basin geometry can play in determining the distribution of sedimentary facies. Admittedly, Demko *et al.* (*op. cit.*) were attempting to introduce a parameter often omitted by others, that of changing sediment flux and its relationship to stream discharge and hence climate, but in doing do they generate a single stratal model, albeit an extremely useful one, applicable only in a particular set of circumstances. It is worth noting that the examples these authors use are taken mainly from relatively stable areas and times (e.g. the Upper

Jurassic Salt Wash Member of the Morrison Formation in Utah) such that the climatic signal is likely to be prominent.

Miall and Arush (2001) have also been cited herein as their concepts of cryptic boundaries within amalgamated fluvial successions, and particularly the methods proposed for the identification of these, also have direct relevance to the Sherwood Sandstone Group. These authors stress the need for detailed sedimentological and petrographical analysis of otherwise apparently monotonous successions and these aspects alone are worthy of comment in their applicability to the discussions in previous sections on the petrographical and geochemical properties of the Sherwood Sandstone. However, Miall and Arush (*op. cit.*) relate the sequence architecture they determine by these methods entirely to tectonically initiated changes in basin geometry and ignore both climatic factors and any potential variations in sediment flux that may have impacted that architecture. They do, however, acknowledge their omission of climatic cyclicity, dismissing this for their purposes in response to their perceived need to place the studied sections into a regional framework. Interestingly, their primary study location is also the Colorado Plateau but in this instance during a more tectonically active period as the concentration is on the Late Cretaceous Castlegate Sandstone.

The final example is taken from Aitken and Flint (1995) who present a model of sequence stratigraphic concepts applicable to fluvial systems examined from the Carboniferous of eastern Kentucky. These authors identify incised valley fills comprising mainly fluvial channel complexes as well as highstand, transgressive and lowstand systems tracts through a total of four lowstand to highstand cycles. Interbedded with the fluvial sandstones are a range of marginal marine sequences including marine shelf, delta plain and interdistributary bay deposits such that it is no surprise to find Aitken and Flint (*op. cit.*) concluding that eustatic sea level changes are the prevailing parameter controlling fluvial sequence architecture. In reality, despite the claims by the authors of this paper in the title and elsewhere that it aims to apply sequence stratigraphic models to the fluvial regime, it in fact presents a classic sequence stratigraphic model for marginal marine clastic environments. The authors comment that previous publications have used syntectonic fault activity to explain facies distributions but then dismiss these in favour of eustasy and,

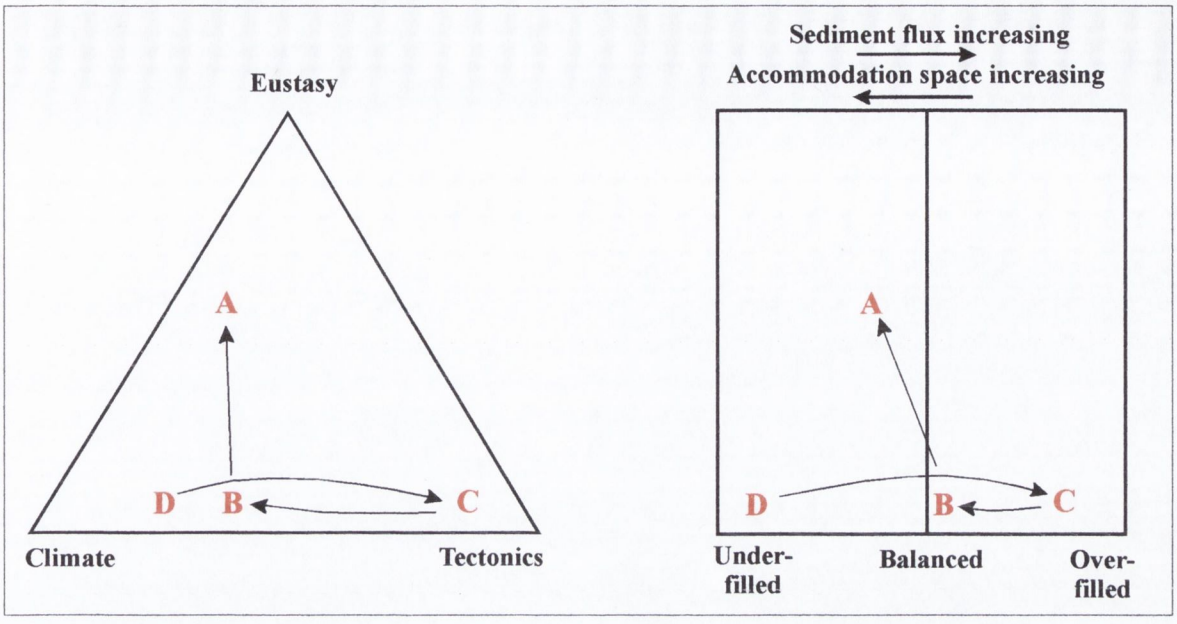


Figure 9.10 Diagrammatic representation of the relationship between the major parameters controlling sequence architecture in continental rocks as applied to the Sherwood Sandstone Group. The figures can be seen as front and side elevations to a three-dimensional trigonal figure. A=Uppermost SSG, B=Upper SSG, C=Lower SSG and D=Basal SSG together with the Barrowmouth Mudstone Formation etc.

equally, do not introduce or acknowledge the potential role of climate change in determining the stratal architecture of the succession.

Each of the three examples mentioned have, to a greater or lesser extent, some relevance to the suggested architecture of the Sherwood Sandstone Group but none of them presents a unifying model that can accommodate the variety of differing geometries that occur within even this one succession of mainly continental rocks. An attempt to overcome this difficulty is presented somewhat simplistically in Figure 9.10 which combines a classic eustasy:tectonics:climate triangle with a realization that the relationship between sediment flux and the rate of creation of accommodation space is critical to predicting sequence architecture. Effectively the two figures are best viewed as the front and side elevations of a three-dimensional trigonal figure such that the deposition of any particular succession of rocks may be influenced to varying degrees by the three major parameters but that this deposition may occur within an under-filled, balanced or over-filled basin. In this view climate, for example, may be the pre-eminent control on deposition at any particular time in a certain basin but the stratal architecture that is preserved will be fundamentally

different depending on the rate at which accommodation space is being created and the rate at which sediment is being input to the basin.

In the case of the Sherwood Sandstone Group, the manner in which these relationships change through time is illustrated by placing the successions discussed above (A,B, C and D) into approximate positions that correspond to their controls. Initially, it seems likely that a series of Permian graben and half graben formed a restricted basin system in which the dominant depositional facies were aeolian dunes and sandsheets with localized playa lakes and minor ephemeral fluvial channels together with alluvial fans that formed around the then basin margins. This suggestion accords with models proposed by Jackson *et al.* (1987) and Jackson and Mulholland (1993) for preservation of Permian successions, essentially Early Permian clastics, within localised structurally controlled basins beneath the more widely preserved and overlapping Triassic succession. A similar model has been proposed for the Celtic Sea and Cardigan Bay Basins (Musgrove *et al.* 1995) where an earliest Triassic palaeo-valley system inherited from Permian rifting is suggested to account for early Sherwood Sandstone Group preservation.

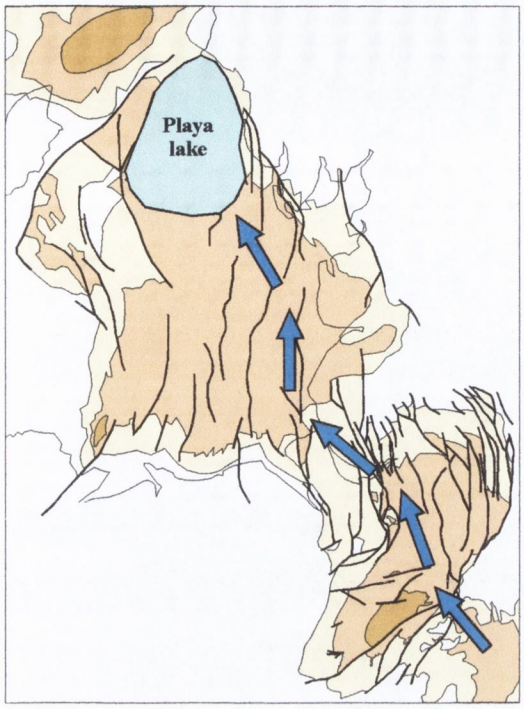
Following the transgression and then retreat of the Late Permian Bakevellia Sea the sediment supply to this basin system was insufficient to keep pace with subsidence and the component basins became progressively more under-filled. Amelioration of the climate in the latest Permian or earliest Triassic facilitated the initiation of a major fluvial system linking the basins and flowing generally northwards through the precursor Cheshire Basin into the East Irish Sea Basin as depicted in Figure 9.11 (1). At this stage the East Irish Sea Basin at least can be regarded as under-filled and, with respect to both the stream discharge and the sediment supply, climatically controlled as depicted by D in Figure 9.10. It appears likely that the Ramsey-Whitehaven Ridge, initially at least, formed a barrier to further northwards flow. The suggested development of an extensive playa lake in the northern parts of the East Irish Sea Basin therefore reflects both the generally south to north palaeo-slope within the basin (*sensu* Jackson and Mulholland 1993) and the increased fluvial discharge associated with the river flowing from the south. Although no longer preserved (or at least exposed) around the present-day basin margins it is likely that local influxes of sediment operating across alluvial fans may have contributed to the gross sediment flux. Such fans are recorded interdigitated with the lowermost Sherwood

Sandstone in the Vale of Eden (Waugh and Macchi 1984), locally sourced grains have been recorded within basal parts of the Sherwood Sandstone in the Carlisle Basin (Holliday *et al.* 2004) and a single alluvial fan is recorded in the present study (Alberbury, Figure 1.5) interdigitated with aeolian sandstones although the stratigraphic position of this latter is uncertain.

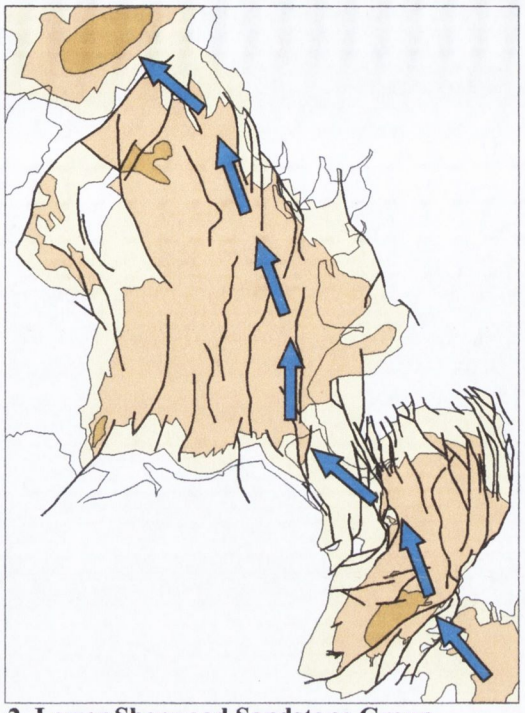
The situation in the Cheshire Basin is less certain as evidence is sparse but the stratal architecture appears to be different and, in the absence of any large playa lakes, it may have been closer to a balanced situation. If this were the case then incision of the fluvial system into previously deposited aeolian and sandflat sequences of the Kinnerton Sandstone Formation could conform to the models proposed for succession B above.

Progradation of the lacustrine fluvio-deltaic sandstones across the East Irish Sea playa lake eventually filled this in completely such that the river was able to exit the basin, probably northwards into the Solway Basin as shown in Figure 9.11 (2). Palaeo-current indicators at Fleswick Bay and St Bees South Head (see logs in Appendix II) are universally northwards, implying that by this time the Ramsey-Whitehaven ridge, on which these localities stand, had been breached. From this time onwards the river system, plus any aeolian input to the area, was always capable of keeping pace with subsidence and the basin system moves within the diagrammatic block to being over-filled with the primary control on stratal architecture changing from being the climate to being the tectonic generation of accommodation space (C). Consequent upon this transition the architecture also changes with no evidence of playa lake or floodplain facies being preserved and results in the deposition of most of the Rottington/Chester Pebble Beds successions.

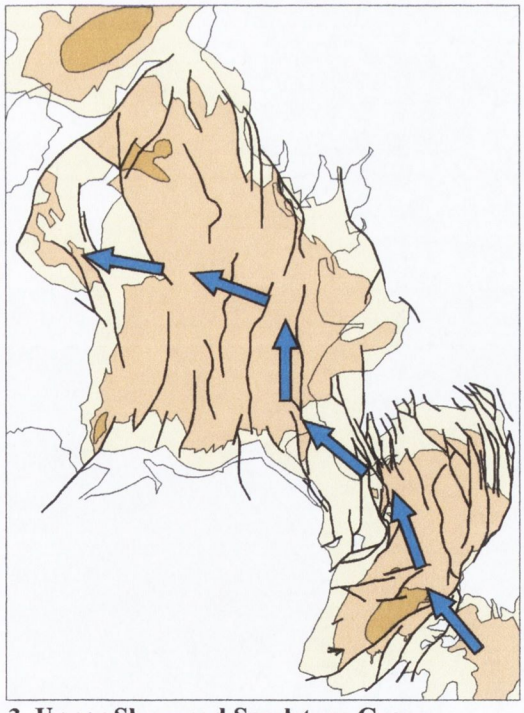
The suggestion that the lower Sherwood Sandstone Group fluvial channel sandstones were deposited within areally constrained basins controlled by active faulting runs counter to models presented by Ruffell and Shelton (1999) who contend that rifting in NW England was restricted to the Early Permian and Mid-Late Triassic. There is, however, ample evidence for early Sherwood Sandstone Group syn-sedimentary thickening into major faults such as the Keys and Formby Point Faults as demonstrated by Jackson *et al.* (1987), Jackson and Mulholland (1993), Knipe *et al.* (1993) and Jackson *et al.* (1995). There is also the evidence from well data where, for example, a comparison can be made between



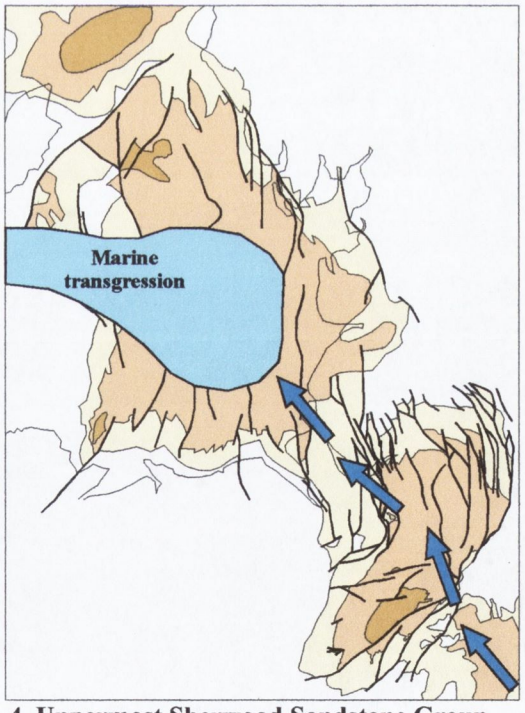
1. Lowermost Sherwood Sandstone Group



2. Lower Sherwood Sandstone Group



3. Upper Sherwood Sandstone Group



4. Uppermost Sherwood Sandstone Group

Figure 9.11 Schematic representation of fluvial channel orientations through Sherwood Sandstone Group depositional time with arrows indicating direction of flow.

the Sherwood Sandstone Group succession penetrated by the Thistleton-1 well (718m) drilled on the footwall of the Formby Point Fault (with the Rottington Member apparently absent, see Appendix I) and basin centre wells such as 113/26-1 (total of 1596m) and 113/27-3 (total of 1292m), that preserve 694m and 575m of Rottington Member respectively. There is little doubt that syn-sedimentary faulting also occurred during Mercia Mudstone Group deposition, as documented by Jackson and Mulholland (1993), but it seems likely that the model proposed by Ruffell and Shelton (1999) represents an over-simplification in the search for broad scale changes in the tectono-sedimentary record.

The next major shift forms probably the most dramatic change to occur within the Sherwood Sandstone Group succession. Either as a result of tectonic enlargement of the basin system or, more likely, as a consequence of the fluvial system finally overtopping the structural limits of the precursor restricted rift basins, the available sedimentary basinal area became significantly larger. Within the subsidence curves proposed by Rowley and White (1998) for the area, this may correspond to the transition from active rifting to regional thermal subsidence. This enlargement shifted the basin system back towards a balanced situation with regard to the relationship between sediment flux and accommodation space and, consequently, the climate again became the over-riding control on stratal architecture. This combination describes the situation that prevailed for the majority of Sherwood Sandstone deposition and accounts for most of the Calder/Wilmslow and Ormskirk/Helsby successions (position B in Figure 9.10). It also seems likely that, consequent on this change, the river ceased to exit the East Irish Sea Basin northwards and instead turned westwards towards the Peel and Kish Bank Basins as shown in Figure 9.11 (3). This inferred change in fluvial channel orientation perhaps suggests that the thermal subsidence operated between the ancestral basin margins, with the notable result that the Ramsey-Whitehaven Ridge appears to have again become a barrier to northwards flow.

The stratal architecture of both fluvial and aeolian/sandflat sequences in succession B provides evidence for a hierarchy of at least three scales of climatic control. In the fluvial system these relate to the apparently episodic infilling of incised valleys, the incision and infilling of the individual valley systems and the overall upward wetting and drying that gave rise to the tripartite stratigraphy of the Ormskirk and Helsby Sandstone Formations. The most distinctive cyclicity in the aeolian/sandflat sequences is that used to support the

climatic model of Demko *et al.* (2002) in Figure 9.6 which would appear to relate to the intermediate member of the fluvial hierarchy. The aeolian/sandflat sequences record a longer term cyclicity, as noted in Figure 3.43, but also record shorter term changes that can be logged over vertical successions of 2-5 m. in core and can be seen in outcrop (Figure 3.42). It is tempting, but almost certainly incorrect, to equate this threefold hierarchy with the three Milankovich parameters and to draw conclusions regarding the relative importance of each to continental sequence architecture. It seems more likely that the three scales of cyclicity represent some combination of the eccentricity, obliquity and precessional components. As the latter two have changed significantly over geological time the interference pattern generated would have been unique to the Early Triassic.

Finally, towards the end of Sherwood Sandstone depositional time the encroaching ?Röt transgression entered the East Irish Sea Basin, probably from the west (Figure 9.11 (4)), and the system shifted once again within the diagrammatic block. For the first time it leaves the base line and eustasy becomes a significant factor in determining the depositional architecture (position A in Figure 9.10). Subsequently, the marine transgression also flooded the Cheshire Basin, effectively terminating Sherwood Sandstone deposition, and there appears to be no further major input of coarse clastic material to either the Cheshire or East Irish Sea Basins for the remainder of the Triassic.

It is tempting to speculate on whether the Sherwood Sandstone fluvial system continued to operate further south, as seems likely given its hinterland in southern Britain and possibly NW France, and if so the potential route and destination for its sediment load. The Bromsgrove Sandstone of Hereford and Worcester, in part equivalent to the Sherwood Sandstone, continues throughout the Triassic to at least the Norian (Warrington *et al.* 1980) but is interdigitated with mudstones. Ruffell and Shelton (1999) suggest renewed rifting the during Mid-Late Triassic, supported by seismic data showing growth faulting accommodated within the Mercia Mudstone Group, coupled with a shift to evaporite and fine grained clastic deposition driven by a change to more arid climatic conditions. Reduced discharge may account for the apparently limited range of the fluvial system during Mercia Mudstone deposition or, alternatively, this may simply reflect a by then eroded source area that no longer had the capacity or elevation to supply large volumes of coarse clastics this far north in the drainage basin.

Of the boundaries between the four successions discussed, that which is most prominent and easiest to both define and identify is the boundary between successions B and C, corresponding to the present tops of the Rottington Member in the East Irish Sea Basin and the Chester Pebble Beds Formation in the Cheshire Basin. On this basis a solution to the inherent problems of the existing stratigraphic nomenclature could be proposed that subdivided the Sherwood Sandstone Group into two formations on this boundary (Figure 9.12). Within the proposed stratigraphy the diachronous nature of both the top and the base of the Sherwood Sandstone Group can be accommodated, mainly by allowing for an interdigitation of the group with the Leyland Formation of the Mercia Mudstone Group

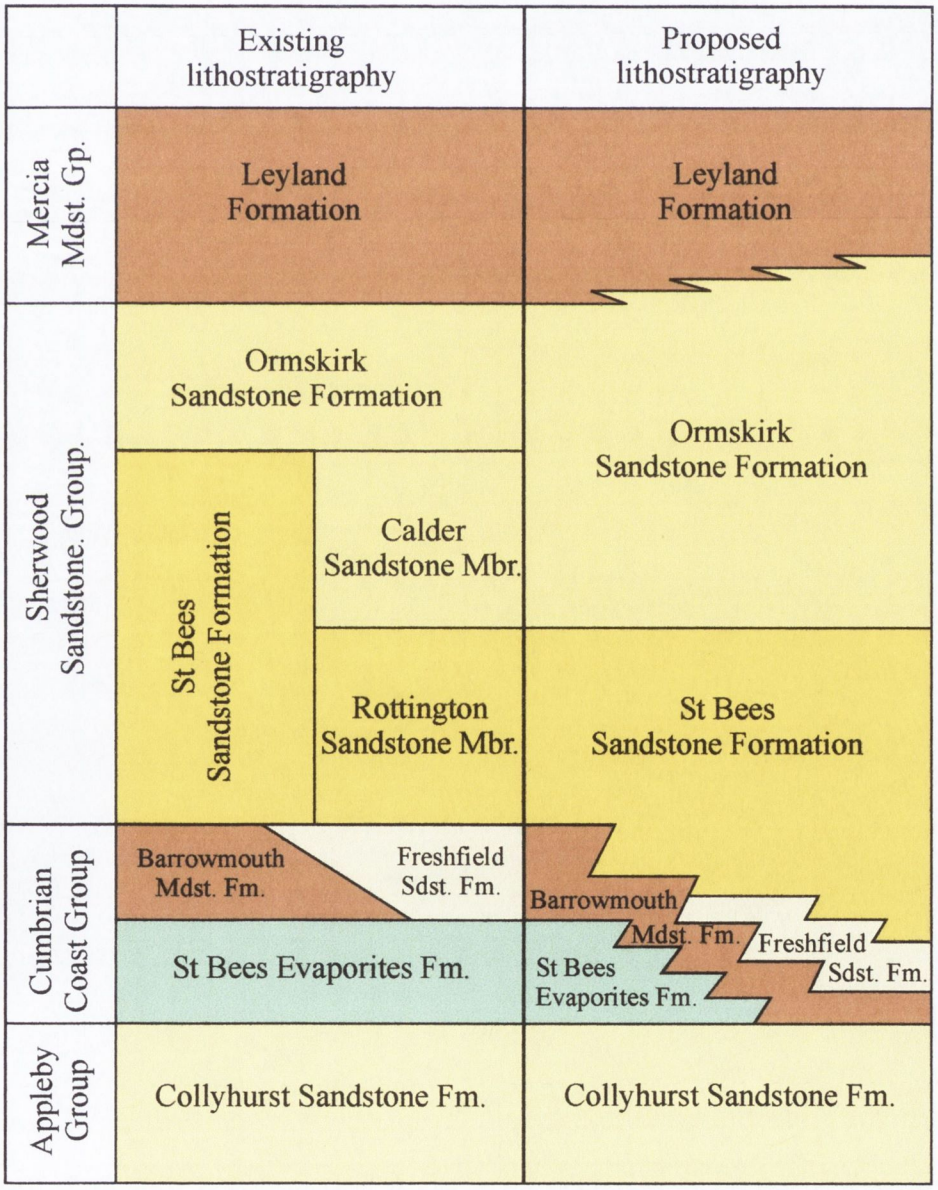


Figure 9.12 Currently accepted and proposed lithostratigraphies for the Sherwood Sandstone Group and associated successions in the East Irish Sea

above and with the Barrowmouth Mudstone Formation of the Cumbrian Coast Group below. The implications of the latter are that the lower parts of the Sherwood Sandstone Group may well span the Permian-Triassic boundary although this time-constrained 'surface' has little or no relevance to the wholly continental and largely barren succession within which it potentially falls in NW England.

From the foregoing discussion it appears likely that this represents the evolution of the Early Triassic basin system from a restricted but interconnected series of rift structures dominated by fluvial activity into much broader, potentially sag, basins preserving a wide range of fluvial, sandflat, aeolian and playa related facies. The stratal architectures above and below this boundary are markedly different and the boundary itself is relatively easy to identify both in wells and on seismic sections.

It is clearly somewhat dangerous to draw too many conclusions on the applicability of sequence stratigraphic concepts to continental rocks from an investigation of one succession in just two of many basins that preserve comparable successions. This investigation of the Sherwood Sandstone Group does, however, serve to illustrate several important points. If no single published model of continental sequence stratigraphy is sufficient to predict the stratal architecture of the Sherwood Sandstone Group then clearly none can yet be capable of predicting such architecture on a global scale. It is however, also apparent that the classic terminology of sequence stratigraphy needs to be modified if it is to serve this purpose for wholly continental rocks. Throughout the majority of the Sherwood Sandstone the terms flooding surface, transgressive or regressive have no meaning. This does not, however, imply that sequences and systems tracts are not present or that sequence boundaries cannot be identified. They certainly are present and they provide the means to better understand and predict the intricacies of continental depositional systems, it is just that the methods of identifying these and using them to effect are different from marine systems and the thought processes involved in unravelling them consequently also need to be different.

10. CONCLUSIONS

The following general conclusions have resulted from this study:

1. The existing stratigraphic nomenclature applied to the Early Triassic Sherwood Sandstone Group in NW England has resulted from more than 150 years of geological investigation. The cumulative consequence of differing perceived needs, or attempts to resolve different specific problems, has over time generated an inconsistent hierarchy of stratigraphic names and a stratigraphic system that fails to allow for variations in lithology and sedimentary facies.

2. The sedimentology of the Sherwood Sandstone Group can be described and interpreted in terms of four depositional environments comprising fluvial channel fills, sandflat including aeolian dunes and sandsheets, floodplains including playa lakes, and alluvial fans. The fluvial channel fills can be divided into six facies that can be related to changing flow conditions within the channels. These comprise high stage bars and compound bars representing the highest stages of flow and bank full conditions, low stage bars and inter-bar channel facies representing progressively lower stages of flow and partial to complete abandonment facies representing the lowest stages of flow and ponding or stagnation within channel anabranches. Sandflats are also divided into six facies types, five of which can be related to variably wet to dry conditions on the depositional surface that were mainly controlled by the relationship between that surface and the palaeo-water table. The facies are termed wet sandflat, damp sandflat, dry sandflat, aeolian sandsheet and aeolian dune and these represent a continuum from wet to dry of sandflat depositional environments. The sixth facies type included in this association is termed clastic sabkha and comprises sandstones interlaminated with marine influenced evaporites. Floodplains are divided into four facies types comprising playa lakes, playa margins, sheetfloods and vegetated floodplains and these can be related to the wettest environmental conditions associated with non-channelised facies. Alluvial fan facies are only positively recorded from one locality in the extreme south of the Cheshire Basin.

3. For the majority of Sherwood Sandstone depositional time a fluvial system operated through the Cheshire and East Irish Sea Basins flowing predominantly northwards from central and southern Britain and exited the East Irish Sea Basin either northwards into the Solway Basin or eastwards towards the Peel and Kish Bank Basins. The fluvial system was of low to moderate sinuosity with an extremely sand-rich bedload comprising mainly fine to medium sand with an exotic pebble component that becomes more sparse northwards and is not found in the northern parts of the East Irish Sea Basin. A subordinate component of medium to coarse well rounded grains is recorded in fluvial channel sandstones but is more common in sandflat and aeolian facies. It is likely that the river exhibited a high discharge ratio with seasonal fluctuations between bank full conditions during which the major bedforms would have migrated and dry season conditions when it was reduced to an anastomosing network of anabranches diverted around the major bars. At times the river will have degenerated into a pool and riffle system with abandonment of some anabranches but it is unlikely to have been ephemeral.

4. Sandflat, floodplain and playa lake facies are interpreted as a continuum of depositional environments coeval with the fluvial channels but operating mainly beyond the reach of the fluvial channel system. At times, and in places where the water table was relatively high, any aeolian processes would have been inhibited and deposition occurred either within standing water bodies or by unconfined fluvial activity. As the water table fell in relation to the sediment surface aeolian processes were initiated and became increasingly dominant. At first these included the adhesion of wind blown sand but further falls in the relative water table led to drying of the surface and the development of wind rippled laminae representing the early stages of aeolian sandsheet formation. Ultimately, as more sand became available, progressively larger aeolian bedforms were generated although the maximum recorded size of aeolian dunes and their common interbedding with other sandflat facies renders it unlikely that large aeolian dune fields were ever developed. The vertical association of aeolian, sandflat and playa related facies suggests a cyclical climatic control on depositional environments with both upward wetting and upward drying transitions being recorded on several scales.

5. The mineralogy of the sandstones is dominated by quartz comprising monocrystalline and polycrystalline forms, the latter exhibiting either equant fabrics suggesting a granitic derivation or schistose fabrics suggesting a metamorphic source. Feldspars include microcline, orthoclase, microperthite and plagioclase and their abundance varies significantly when plotted downwell but does not appear to relate to the existing stratigraphy. Rock fragments are dominated by compound grains comprising quartz, feldspar and occasionally mica that can exhibit either equant or schistose fabrics similar to the quartz grains. Grains suggested to derive from a metamorphic source range from low grade chloritised sandstones to high grade mica schists. The proportion of granitic to metamorphic grains in the sandstones varies systematically and also has stratigraphic implications. The heavy mineral assemblage is dominated by tourmaline, zircon and apatite with minor rutile, monazite and pyroxene. There are peaks in the absolute abundance of heavy minerals that can not be related to depositional processes or sedimentary facies and are suggested to represent influxes of sand rich in these minerals.

6. The detrital geochemistry of the sandstones, as determined by ICP-AES and ICP-MS analysis of samples from four wells, is subject to a lithological control dependent on the clay content of the sandstones that has necessitated normalization of the data. Following normalization, downwell plots of Al_2O_3, K_2O and Na_2O reveal similar stratigraphic variations in abundance to that observed for feldspars, while TiO_2, Y, Zr, La and Ce closely match the downwell abundances of the heavy mineral assemblage. The most noticeable characteristics of the chemical dataset are a marked upward increase in feldspar related oxides within the upper parts of the Ormskirk Sandstone Formation and the presence of three prominent peaks in the trace element data through the same interval. The stratigraphic distribution of these changes is the same in all four wells but, as with the mineralogical data, does not relate to either sedimentary facies or the existing stratigraphy.

7. A revised well correlation is proposed for the Ormskirk Sandstone Formation in the East Irish Sea Basin that is based upon the mineralogical and chemical variations and, in particular, uses the marked upward increase in the feldspar content of the

sandstones as a datum. The correlation is extended from the four analysed wells across the East Irish Sea Basin using the close correspondence of the feldspar datum to a readily identified and extensive playa lake sequence. This correlation implies diachroneity at the top Sherwood Sandstone to Mercia Mudstone Group contact, effectively proving previously unsupported suggestions. The revised correlation of fluvial channel sequences reveals the presence of major incision surfaces above which stacked amalgamated fluvial channel sandstones tend to be concentrated and also shows the presence of isolated fluvial channel fills surrounded by sandflat facies. A combination of well sections orientated broadly NNW-SSE and W-E suggests that the incised valleys within which the channel fills are stacked were cut by a fluvial system flowing from the Cheshire Basin northwards and then westwards to exit the East Irish Sea Basin towards the Peel and Kish Bank Basins. A similar sequence architecture is proposed for the Cheshire Basin based on facies distributions but is unconstrained by mineralogical and chemical data. The potential presence of incised valley fills may account for previous suggestions regarding an intra-Sherwood Sandstone unconformity based on outcrop and seismic data.

8. Similar facies distributions to those identified and correlated in the Ormskirk and Helsby Sandstone Formations are recorded in the underlying Calder Sandstone Member and Wilmslow Sandstone Formation in the East Irish Sea and Cheshire Basins respectively. Although also unconstrained by mineralogical and chemical data, the proposed correlations indicate a broadly similar stratal architecture and orientation of incised valleys in the Calder Member to that proposed for the Ormskirk Sandstone Formation.

9. The Rottington Member and the Chester Pebble Beds Formation are characterised by vertically stacked fluvial channel sequences with little or no preservation of associated non-channelised facies. Despite high levels of heterogeneity in the vertical and lateral amalgamation of individual fluvial channel fills, laterally extensive surfaces can be identified that bound packages of fluvial channel sandstones. These surfaces are compound in that they comprise the cumulative effect of numerous channel bases, each of which has cut to approximately the same

level within the succession and therefore contributes to the overall near planar geometry of the surface. At the base of the Rottington Member in the northern East Irish Sea Basin the sandstones of the Sherwood Sandstone are interdigitated with claystones and siltstones of the supposed underlying Barrowmouth Mudstone Formation. This relationship is apparent at outcrop in west Cumbria and is revealed in offshore wells by using the presence of Late Permian evaporites as a datum. The facies are interpreted as relating to an extensive playa lake into which the sandstones of the Sherwood Sandstone Group prograded as lacustrine fluvio-deltaic facies until such time as they succeeded in filling the pre-existing basin and the fluvial system responsible exited the East Irish Sea Basin northwards into the Solway Basin.

10. Four distinct stratal geometries are apparent within the Sherwood Sandstone Group based upon the revised sedimentological interpretations and correlations. The uppermost part of the group includes marine influenced clastic sabkha facies and exhibits a stratal architecture similar to that predicted for retrogradational marginal marine parasequences by existing sequence stratigraphic models. The upper parts of the group, including most of the existing Ormskirk, Helsby, Calder and Wilmslow Sandstones is characterised by the presence of incised valley fills cut into sandflat and aeolian facies. In the absence of any evidence to support a eustatic control on this architecture it is related to a climatically mediated control on the relationship between sediment flux and stream discharge in the fluvial system. This generated alternating episodes of fluvial degradation and aggradation in which the fluvial system repeatedly eroded previously deposited sediments to cut an incised valley in response to a high stream discharge and then, confined within this incised valley, aggraded rapidly in response to a rise in sediment flux to generate the stacked amalgamated channel fills. This hypothesis is supported by the correspondence of incision surfaces with upward wetting sequences defined by cyclical facies variations in the sandflat and aeolian facies. The lower parts of the Sherwood Sandstone Group, corresponding to the majority of the present Rottington Sandstone and Chester Pebble Beds are characterised by laterally extensive surfaces bounding packages of highly heterogeneous fluvial channel sandstones. The packages and their bounding surfaces are suggested to represent a

tectonic control on the creation of accommodation space with episodes of quiescence allowing time for channel migration across a significant area of the more restricted basin system present at this time. The basal Sherwood Sandstone Group, where it is interbedded with the Barrowmouth Mudstone Formation, exhibits a stratal architecture that conforms to model that predict the geometry of progradational parasequence sets in a marginal marine environment and is suggested to represent the lacustrine equivalent of this model.

11. Published models of continental sequence stratigraphy tend to concentrate on one of the three main controlling parameters; climate, tectonics or eustasy, in attempts to render comprehensible the complexity of interacting continental depositional systems. This can lead to over-simplification, especially in the case of the Sherwood Sandstone Group where all three parameters have played a role to varying degrees in determining the gross stratigraphic architecture. A simple model is proposed that allows the relationship between sediment flux and the rate of creation of accommodation space to be visualised with respect to the interplay between climate, tectonics and eustasy such that different basins, or the same basin at different times, can be viewed as under-filled, balanced or over-filled. It is apparent that relatively subtle changes in these relationships can have profound effects on the preserved stratal architecture. It is proposed that, rather than the present three-fold subdivision of the Sherwood Sandstone Group, it would be more valid to divide it into two formations, the boundary between the two corresponding to the currently defined top of the Rottington Sandstone Member and Chester Pebble Beds Formation in the East Irish Sea and Cheshire Basins respectively. This surface is readily identified in wells and on seismic sections and is suggested to represent the transformation of the basin system from restricted but interconnected rift structures to regional sag basins.

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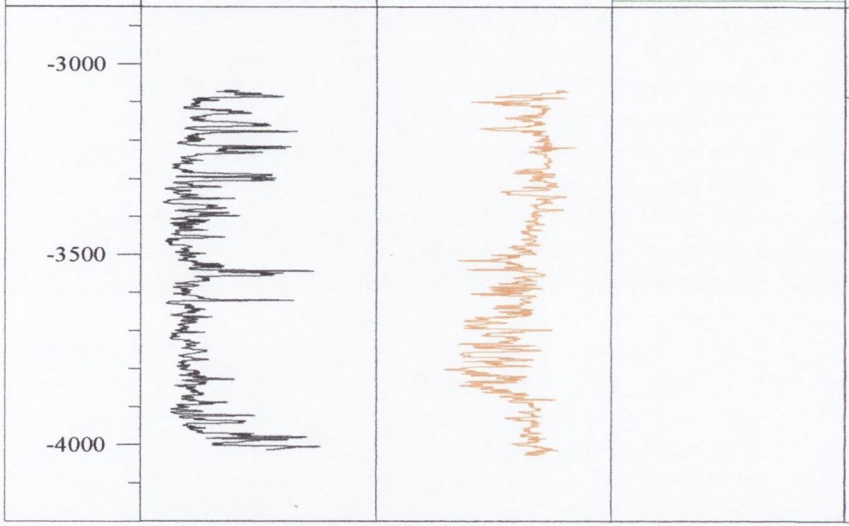
APPENDIX I

Well Sections (1:6000 scale)

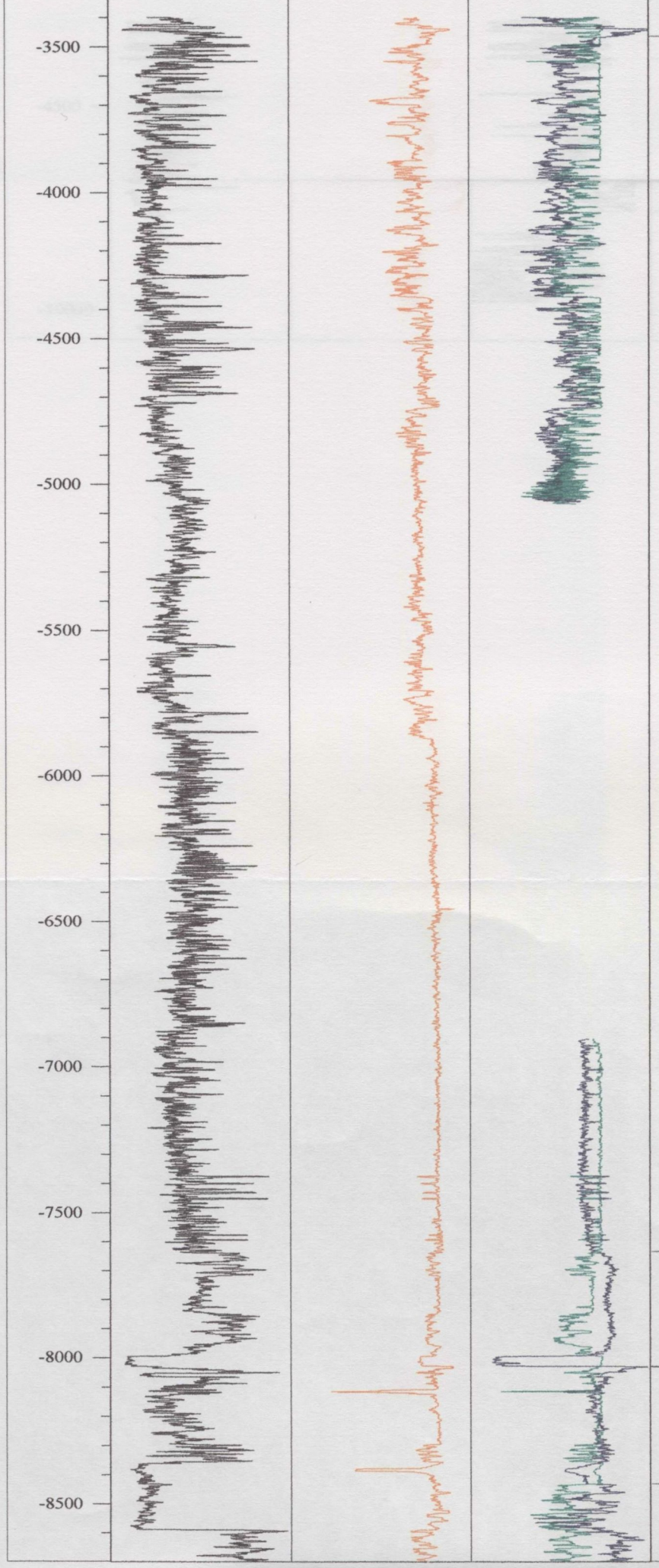
110/2-6

Scale: 1:6000



Lithostratigraphy				
Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			3088.0	941.20
Sherwood Sandstone >289.90m	Ormskirk Sdst 243.25m	OS2b 118.60m	3477.0	1059.80
		OS2a 44.50m	3623.0	1104.30
		OS1 80.15m	3886.0	1184.45
	St Bees Sdst >46.65m	Calder Sdst >46.65m		
TD			4039.0	1231.10

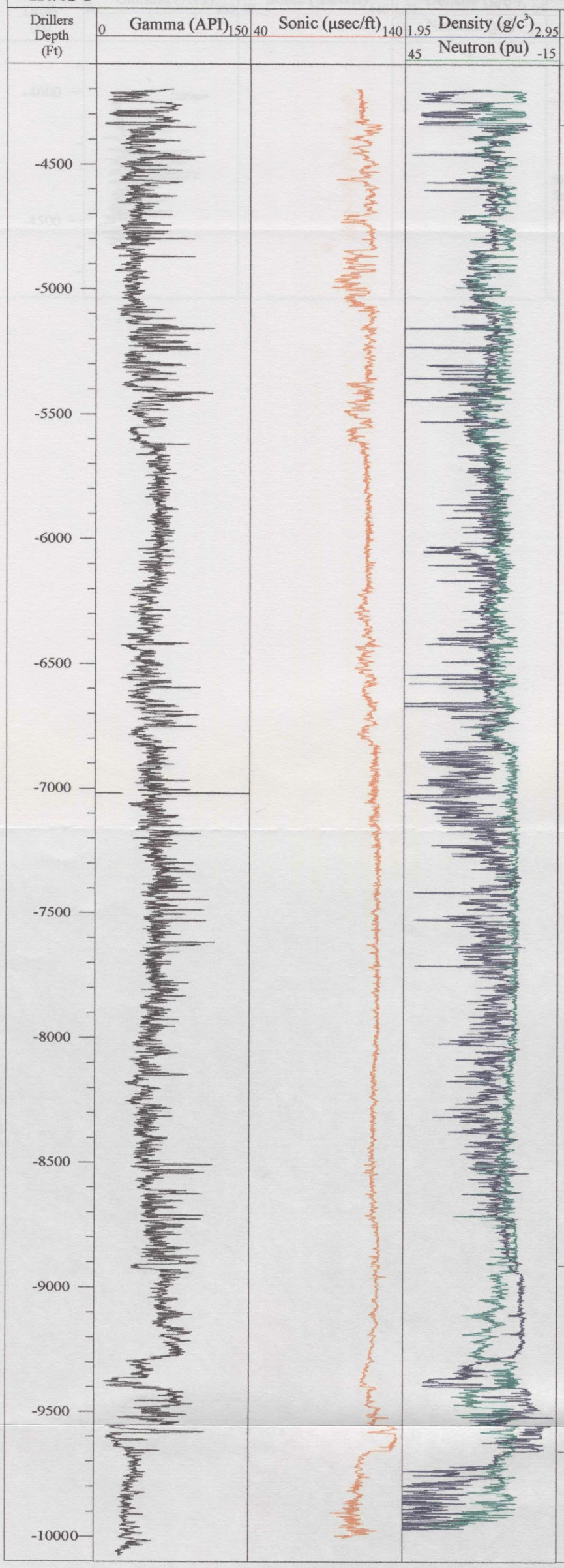
110/2b-9 Scale: 1:6000



Lithostratigraphy

Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			3469.0	1057.35
Sherwood Sandstone 1271.35m		OS2 56.95m	3656.0	1114.30
	Ormskirk Sdst 270.35m	OS1 213.40m	4356.0	1327.70
	St Bees Sdst 1001.00m	Calder 461.50m	5870.0	1789.20
		Rottington Sdst 539.50m	7640.0	2328.70
Cumbrian Coast 118.85m	Barrowmouth Mdst 70.70m		7990.0	2435.35
	St Bees Evaporites 12.20m		8030.0	2447.55
Appleby 123.15m	Collyhurst 123.15m		8434.0	2570.70
Carb.				

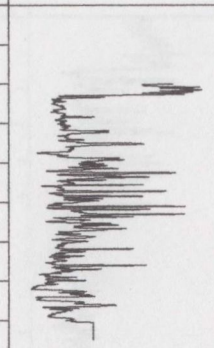
110/6b-1 Scale: 1:6000



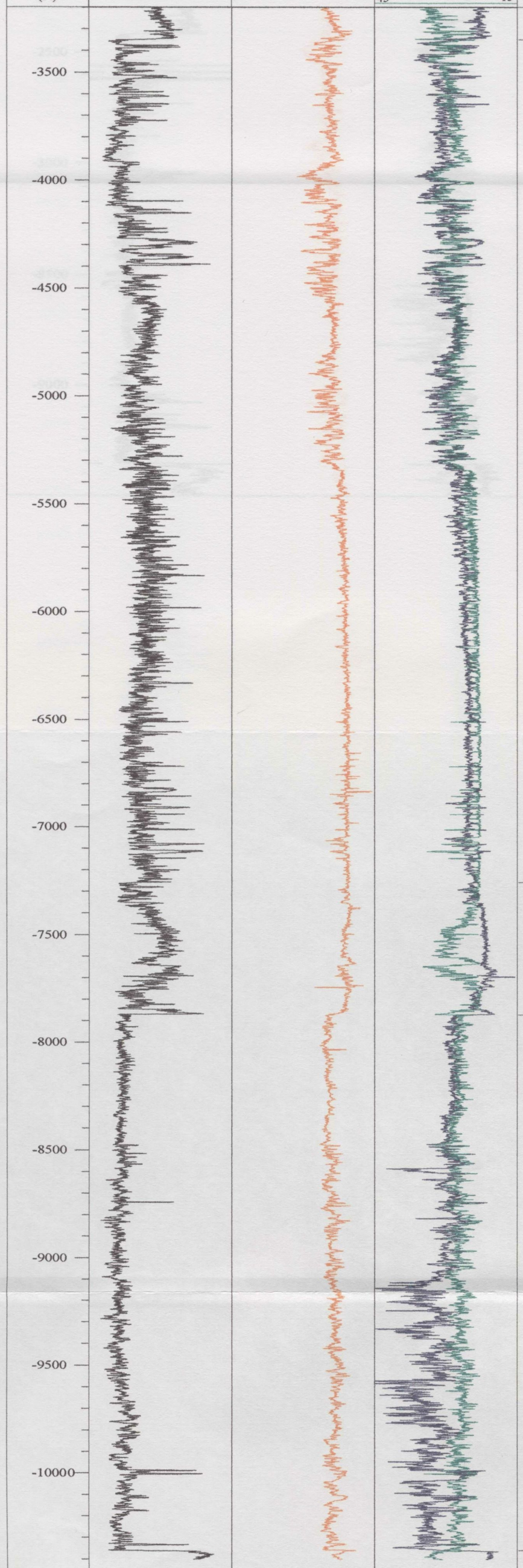
Lithostratigraphy

Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			4342.0	1323.45
Sherwood Sandstone 1392.30m	Ormskirk Sdst 221.25m	? OS2b 44.20m	4487.0	1367.65
		? OS2a 108.50m	4843.0	1476.15
		? OS1 68.55m	5068.0	1544.70
	St Bees Sdst 1171.05m	Calder 536.45m	6828.0	2081.15
		Rottington Sdst 634.60m	8910.0	2715.75
Cumbrian Coast 227.40m	Freshfield Sdst 6.10m		8930.0	2721.85
	Barrowmouth Mdst 132.00m		9363.0	2853.85
	St Bees Evaporites 89..30m		9656.0	2943.15
Appleby >133.80m	Collyhurst >133.80m		10095.0	3076.95
TD				

110/8a-5 Scale: 1:6000

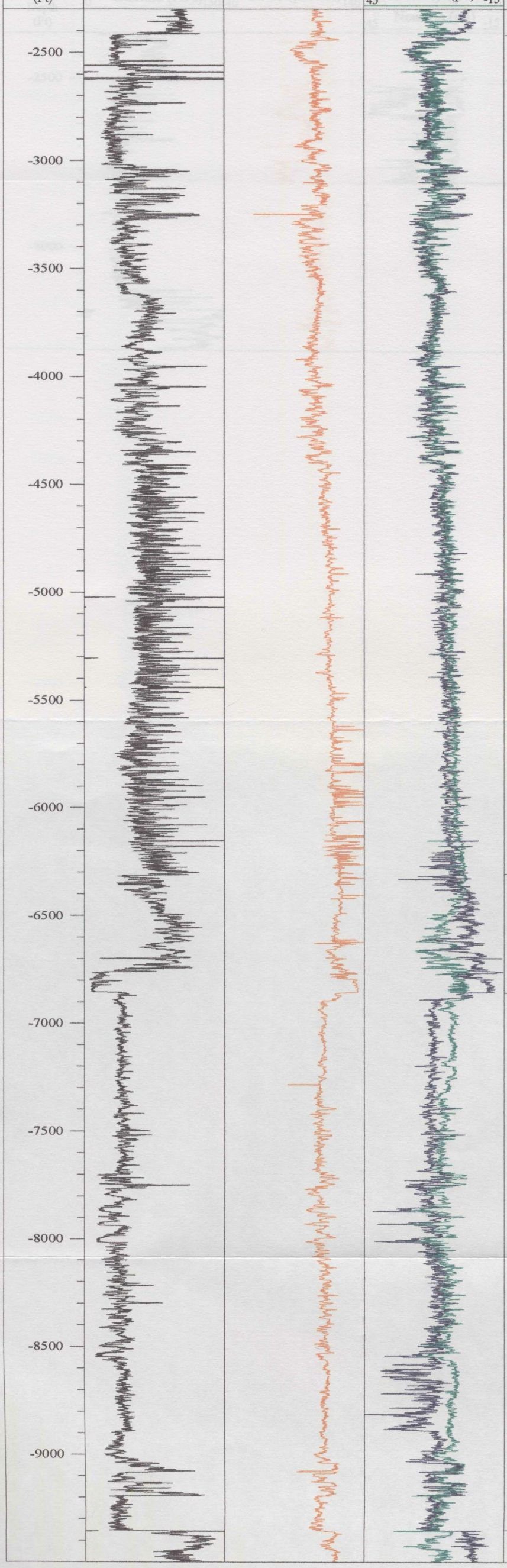
Drillers Depth (Ft)	Gamma (API) 0–150	Sonic (µsec/ft) 40–140	Density (g/c³) 1.95–2.95 / Neutron (pu) 45–-15	Group	Formation	Member	Depth (Ft)	Depth (m)
-4000				Mercia Mdst			4027.0	1227.40
				Sherwood Sandstone >189.60m	Ormskirk Sdst 175.60m	OS2b 48.50m	4186.0	1275.90
						OS2a 65.85m	4402.0	1341.75
-4500						OS1 61.25m	4603.0	1403.00
				TD	St Bees Sdst >14.00m	Calder Sdst >14.00m	4649.0	1417.00

110/11-1 Scale: 1:6000



Lithostratigraphy				
Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			3349.0	1020.80
Sherwood Sandstone 1192.05m	Ormskirk Sdst 232.55m	? OS2b 44.20m	3531.0	1076.25
		? OS2a 118.25m	3919.0	1194.50
		? OS1 58.85m	4112.0	1253.35
		Calder 376.75m	5348.0	1630.10
	St Bees Sdst 959.50m	Rottington Sdst 582.75m	7260.0	2212.85
Cumbrian Coast 185.95m	Freshfield Sdst 28.35m		7353.0	2241.20
	Barrowmouth Mdst 157.80m		7870.0	2398.80
Appleby 758.95m	Collyhurst 758.95m		10360.0	3157.75
Carb.				

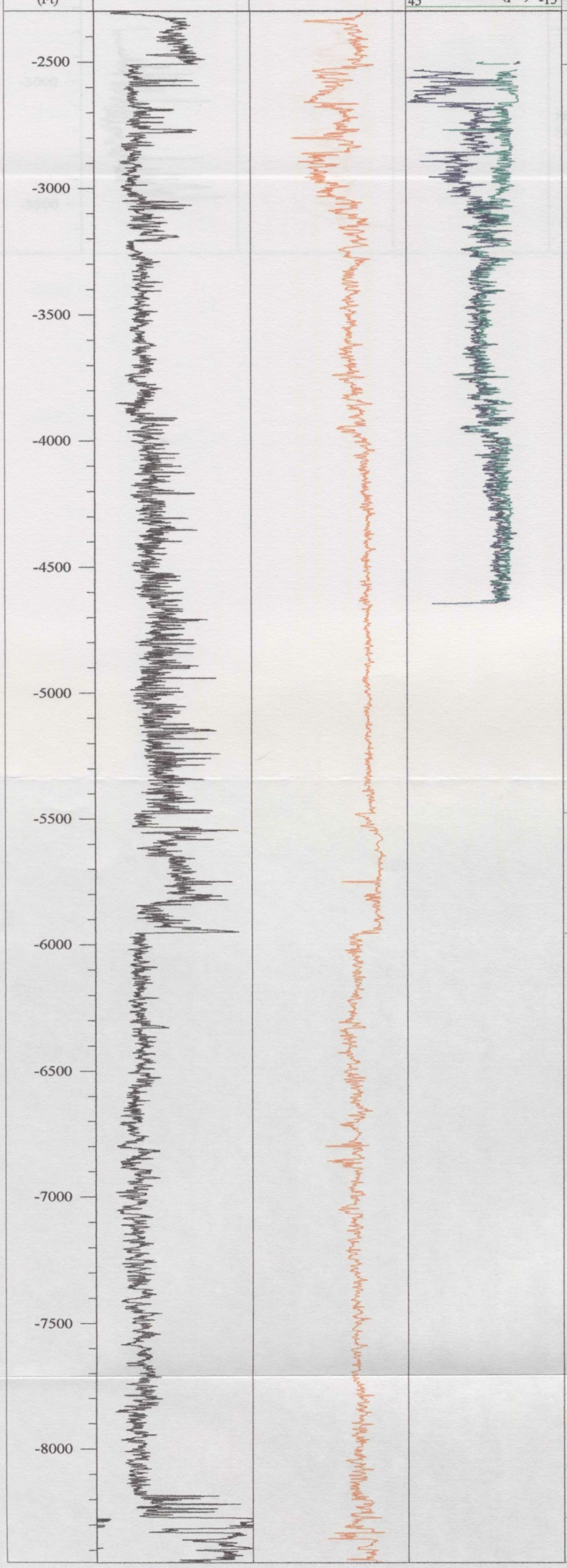
110/12a-1 Scale: 1:6000



Lithostratigraphy

Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			2408.0	733.95
Sherwood Sandstone 1189.95m	Ormskirk Sdst 186.55m	? OS2b 39.35m	2537.0	773.30
		? OS2a 116.70m	2902.0	884.50
		? OS1 36.00m	3020.0	920.50
		Calder 423.10m	4408.0	1343.60
	St Bees Sdst 1003.40m	Rottington Sdst 580.30m	6312.0	1923.90
Cumbrian Coast 164.60m	Freshfield Sdst 32.90m		6420.0	1956.80
	Barrowmouth Mdst 91.45m		6720.0	2048.25
	St Bees Evaporites 40.25m		6852.0	2088.50
Appleby 762.60	Collyhurst 762.60m		9354.0	2851.10
Carb.				

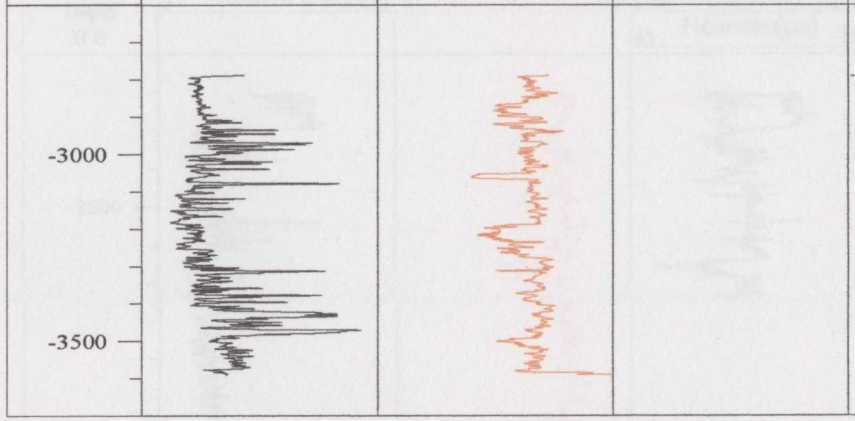
110/13-1 Scale: 1:6000



Lithostratigraphy

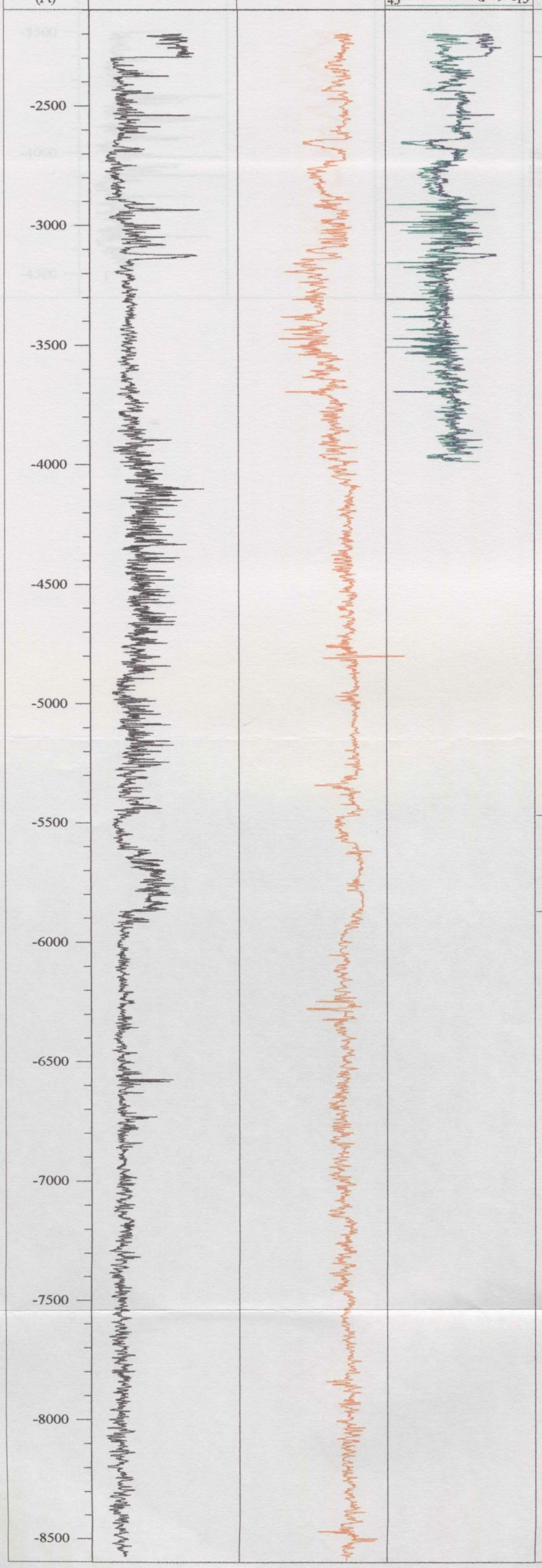
Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			2510.0	765.05
Sherwood Sandstone 903.75m	Ormskirk Sdst 164.90m	OS2b 53.65m	2686.0	818.70
		OS2a 51.50m	2855.0	870.20
		OS1 59.75m	3051.0	929.95
	St Bees Sdst 738.85m	Calder 260.60m	3906.0	1190.55
		Rottington Sdst 478.25m	5475.0	1668.80
Cumbrian Coast 144.75m	Freshfield Sdst 16.45m		5529.0	1685.25
	Barrowmouth Mdst 128.30m		5950.0	1813.55
Appleby 707.75m	Collyhurst 707.75m		8272.0	2521.30
Carb.				

110/13-5 Scale: 1:6000



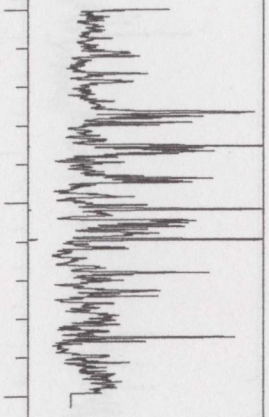
Lithostratigraphy				
Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			2790.0	850.40
Sherwood Sandstone >253.85m	Ormskirk Sdst 157.55m	OS2b 44.20m	2935.0	894.60
		OS2a 76.50m	3186.0	971.10
		OS1 36.85m	3307.0	1007.95
	St Bees Sdst >86.30m	Calder Sdst >86.30m		
TD			3590.0	1094.25

110/13-12 Scale: 1:6000



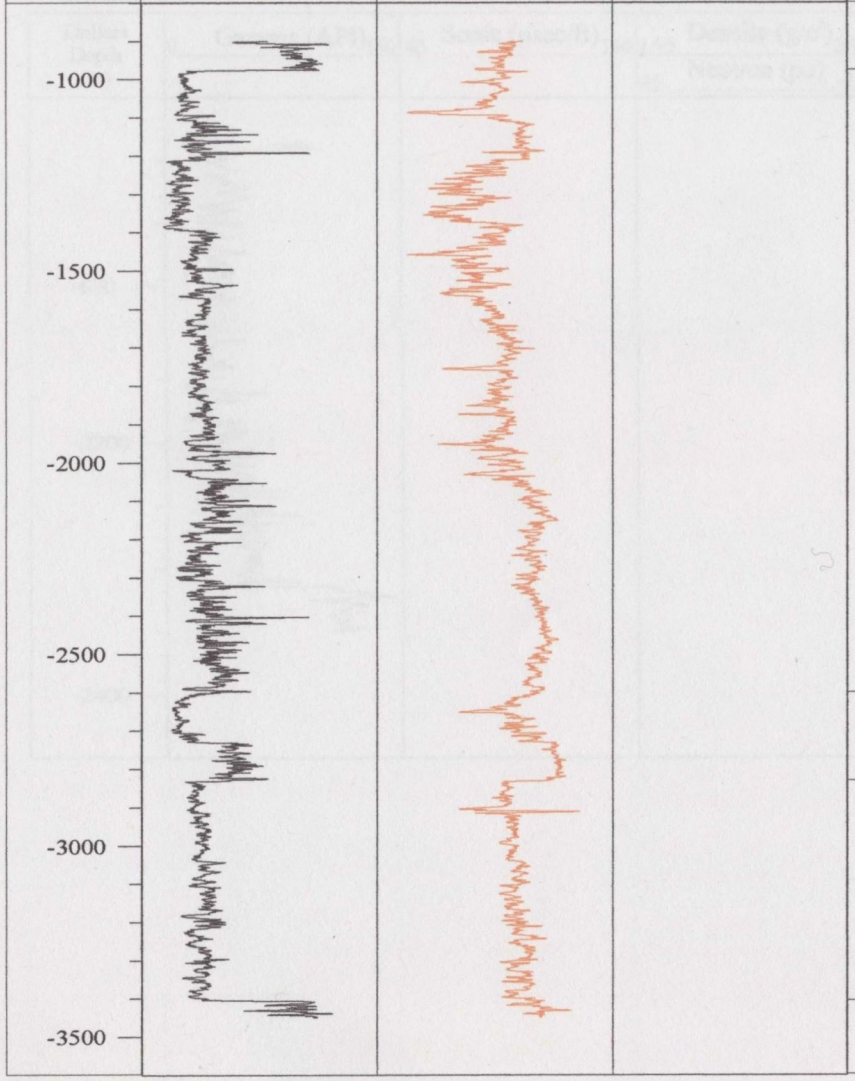
Lithostratigraphy				
Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			2296.0	699.80
Sherwood Sandstone 967.45m	Ormskirk Sdst 178.00m	OS2b 43.30m	2438.0	743.10
		OS2a 61.55m	2640.0	804.65
		OS1 73.15m	2880.0	877.80
	St Bees Sdst 789.45m	Calder 368.20m	4088.0	1246.00
		Rottington Sdst 421.25m	5470.0	1667.25
Cumbrian Coast 122.55m	Freshfield Sdst 55.80m		5653.0	1723.05
	Barrowmouth Mdst 66.75m		5872.0	1789.80
Appleby >828.75m	Collyhurst >828.75m			
TD			8591.0	2618.55

110/14-3 Scale: 1:6000

Drillers Depth (Ft)	Gamma (API) 0–150	Sonic (µsec/ft) 40–140	Density (g/c³) 1.95–2.95 / Neutron (pu) 45–-15
-3500			
-4000			
-4500			

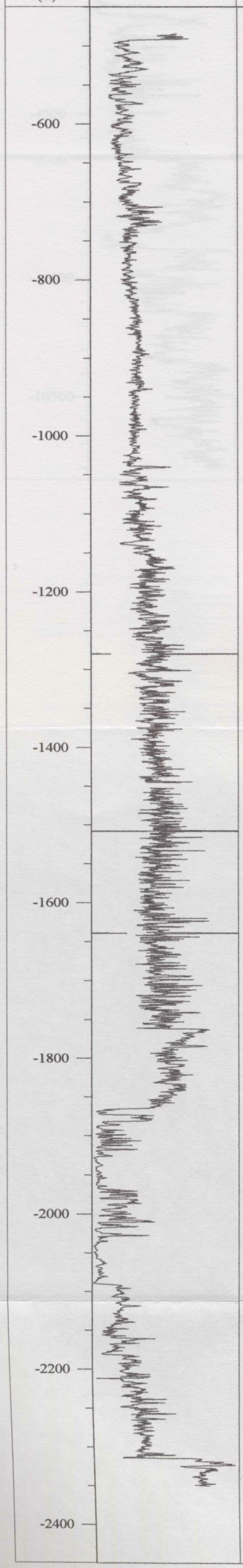
Lithostratigraphy				
Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			3501.0	1067.10
Sherwood Sandstone >313.65m	Ormskirk Sdst 257.35m	OS2b 79.55m	3762.0	1146.65
		OS2a 115.85m	4142.0	1262.50
		OS1 61.95m	4346.0	1324.45
TD	St Bees Sdst >56.30m	Calder Sdst >56.30m	4530.0	1380.75

110/20-1 Scale: 1:6000



Lithostratigraphy				
Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			975.0	297.20
Sherwood Sandstone 496.80m	Ormskirk Sdst 128.00m	OS2b 36.55m	1095.0	333.75
		OS2a 35.65m	1212.0	369.40
		OS1 55.80m	1395.0	425.20
	St Bees Sdst 368.80m	Calder Sdst 165.90m	1940.0	591.10
		Rottington Sdst 202.90m	2605.0	794.00
Cumbrian Coast 69.20m	Freshfield Sdst 38.70m		2732.0	832.70
	Barrowmouth Mdst 30.50m		2832.0	863.20
Appleby 174.95m	Collyhurst 174.95m		3406.0	1038.15
Carb				

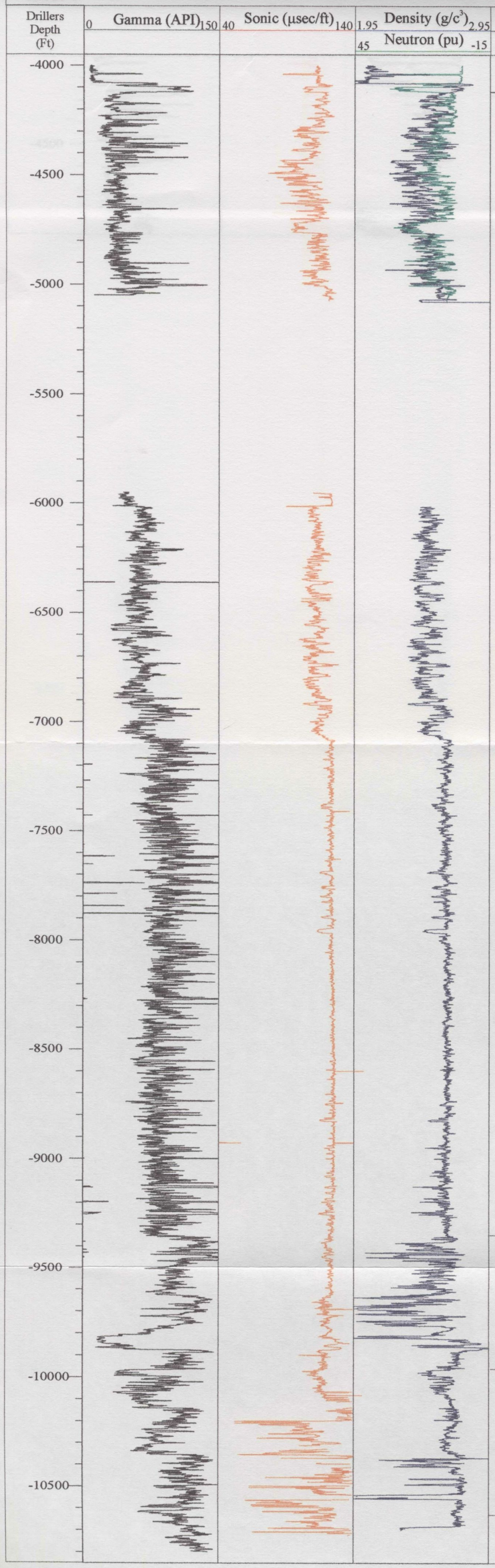
112/25a-1 Scale: 1:6000



Lithostratigraphy				
Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			1611.0	491.00
Sherwood Sandstone 967.45m		? OS2b 215.00m		
	Ormskirk Sdst 334.00m		2316.0	706.00
		? OS2a 41.00m	2451.0	747.00
		? OS1 78.00m	2707.0	825.00
		Calder 253.00m	3537.0	1078.00
	St Bees Sdst 789.45m			
		Rottington Sdst 683.00m	5778.0	1761.00
Cumbrian Coast 330.00m	Barrowmouth Mdst 105.00m		6122.0	1866.00
	St Bees Evaporites 225.00m		6860.0	2091.00
Appleby 223.00m	Collyhurst 223.00m		7592.0	2314.00
Carb				

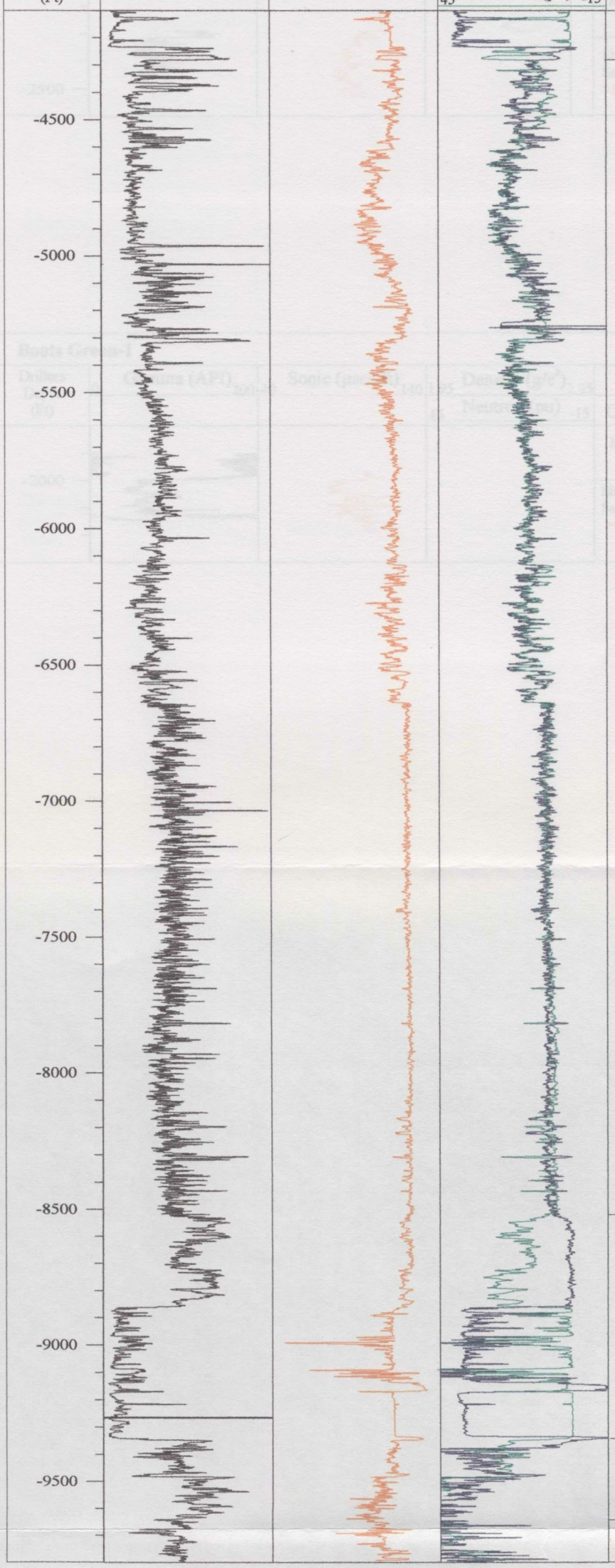
113/26-1

Scale: 1:6000



Lithostratigraphy				
Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			4121.0	1256.10
Sherwood Sandstone 1596.20m		OS2 48.15m	4279.0	1304.25
	Ormskirk Sdst 238.05m	OS1 189.90m	4902.0	1494.15
		Calder 663.85m		
	St Bees Sdst 1358.15m		7080.0	2158.00
		Rottington Sdst 694.30m	9358.0	2852.30
Cumbrian Coast 185.05m	Barrowmouth Mdst 136.85m		9807.0	2989.15
	St Bees Evaporites 48.20m		9965.0	3037.35
Appleby 224.00m	Collyhurst 224.00m		10700.0	3261.35
Carb.				

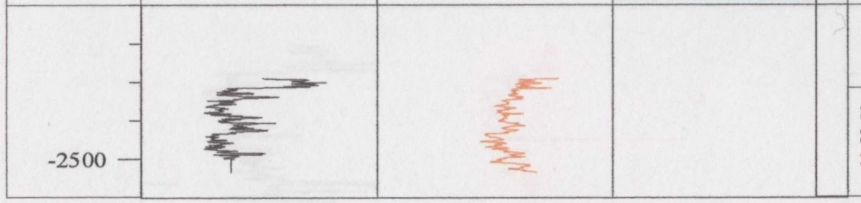
113/27-3 Scale: 1:6000



Lithostratigraphy

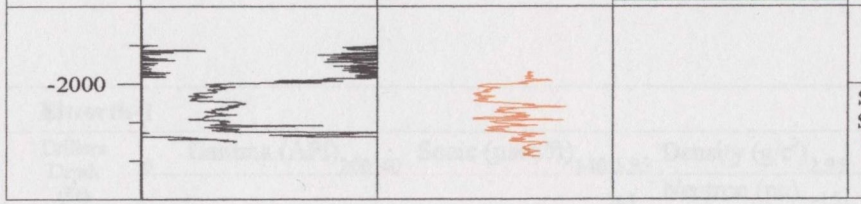
Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			4282.0	1305.15
Sherwood Sandstone 1292.95m				
	Ormskirk Sdst 216.40m	? OS2 98.45m	4605.0	1403.60
		? OS1 117.95m	4992.0	1521.55
		Calder 501.40m	6637.0	2022.95
	St Bees Sdst 1076.55m			
		Rottington Sdst 575.15m	8524.0	2598.10
Cumbrian Coast 250.85m	Barrowmouth Mdst 103.05m		8862.0	2701.15
	St Bees Evaporites 147.80m		9347.0	2848.95
Appleby 83.25m	Collyhurst 83.25m		9620.0	2932.20
Carb.				

Blakenhall-1 Scale: 1:6000



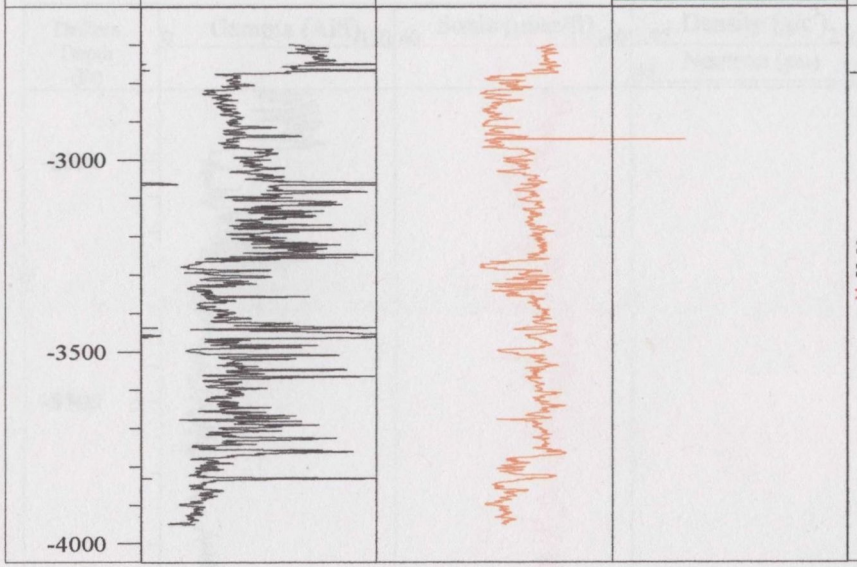
Lithostratigraphy				
Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			2314.0	972.00
Sherwood Sandstone >110.00m	Helsby Sdst >110.00m	? Frodsham Sdst 83.00m	2512.0	1055.00
		? Delamere Sdst >27.00m	2577.0	1082.00
TD				

Boots Green-1 Scale: 1:6000



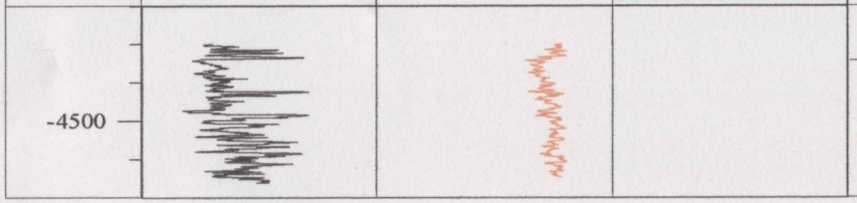
Lithostratigraphy				
Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			2000.0	610.00
Sherwood Sandstone >69.00m	Helsby Sdst >69.00m	Frodsham Sdst 38.00m	2152.0	648.00
		? Delamere Sdst >31.00m	2227.0	679.00
TD				

Burford-1 Scale: 1:6000



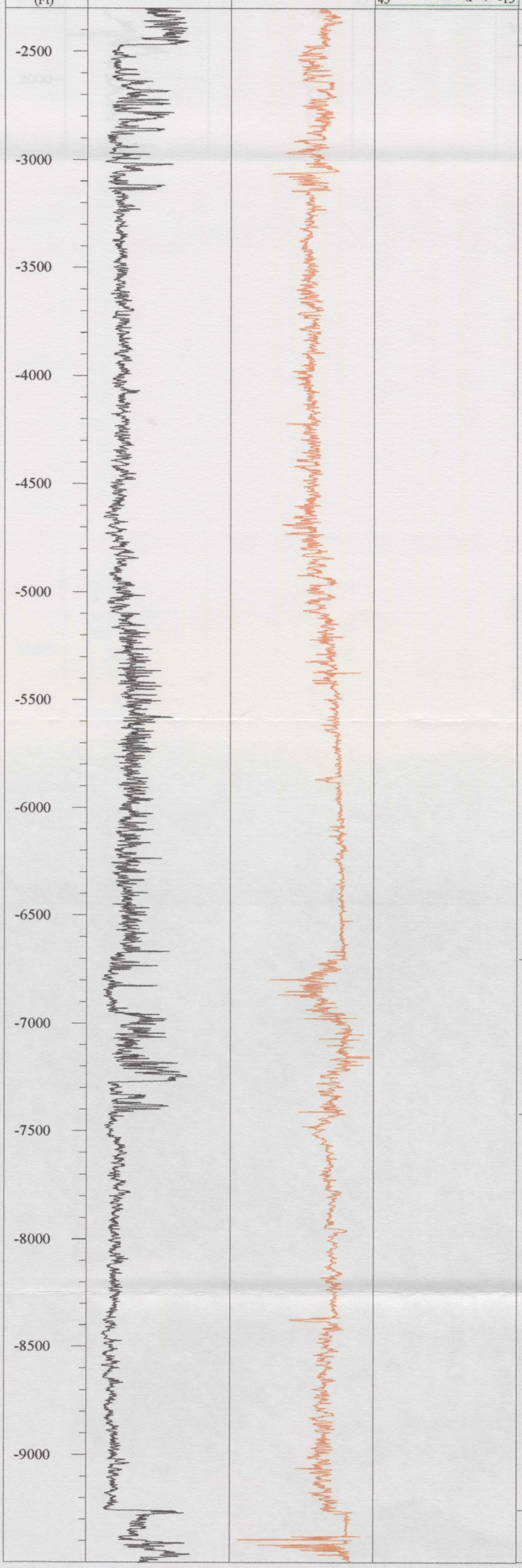
Lithostratigraphy				
Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			2772.0	845.00
Sherwood Sandstone >363.00m	Helsby Sdst 202.00m	Frodsham Sdst 88.00m	3060.0	933.00
		Delamere Sdst 61.00m	3260.0	994.00
		Thursaston Sdst 53.00m	3435.0	1047.00
	Wilmslow Sdst >161.00m			
TD			3964.0	1208.00

Elworth-1 Scale: 1:6000



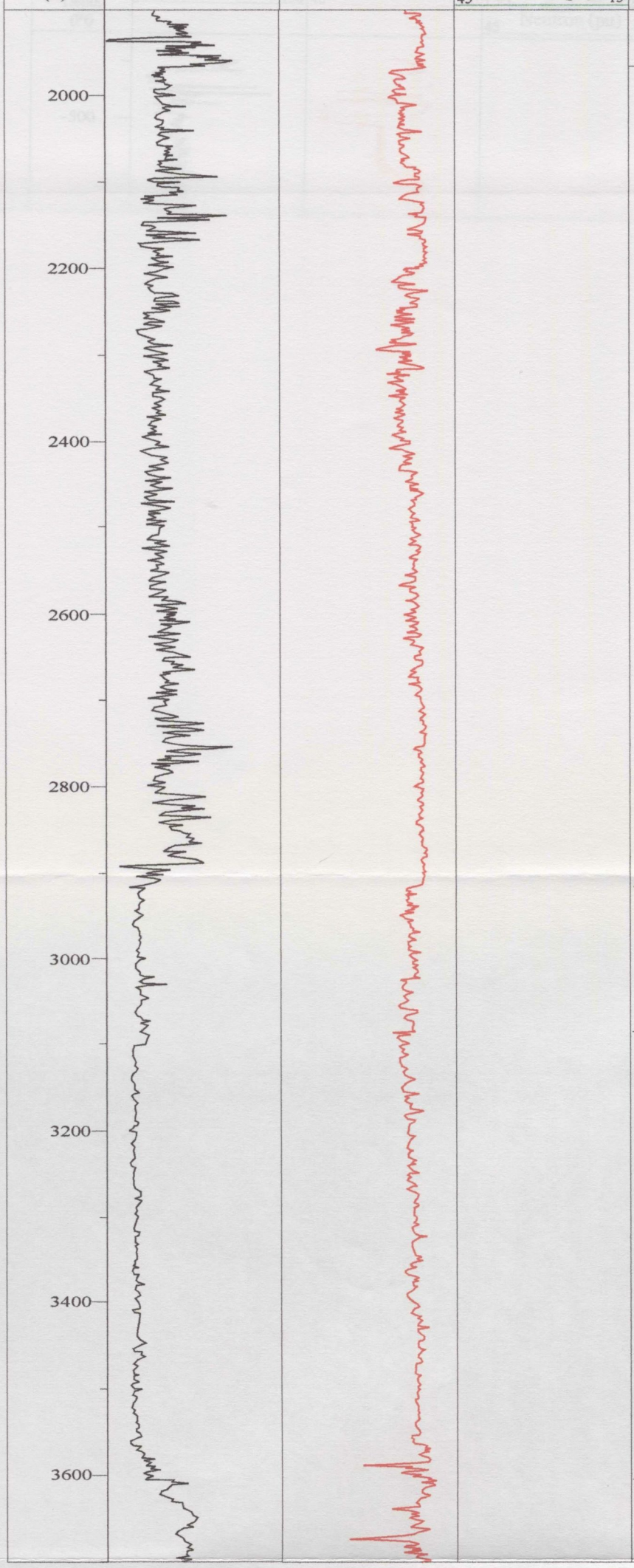
Lithostratigraphy				
Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			4338.0	1322.00
Sherwood Sandstone >100.00m	Helsby Sdst >100.00m	? Frodsham Sdst 44.00m	4483.0	1366.00
		? Delamere Sdst >56.00m		
TD			4665.0	1422.00

Knutsford-1 Scale: 1:6000



Lithostratigraphy				
Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			2468.0	752.25
Sherwood Sandstone 1290.50m	Helsby Sdst 201.45m	Frodsham Sdst 50.30m	2633.0	802.55
		Delamere Sdst 71.05m	2866.0	873.55
		Thurstaston Sdst 80.15m	3129.0	953.70
	Wilmslow Sdst 599.25m		5095.0	1552.95
	Chester Pebble Beds 489.80m		6702.0	2042.75
Cumbrian Coast 212.15m	Kinnerton Sdst 77.15m		6955.0	2119.90
	Manchester Marl 135.00m		7398.0	2254.90
Appleby 566.95m	Collyhurst Sdst 566.95m		9258.0	2821.85
Carb.				

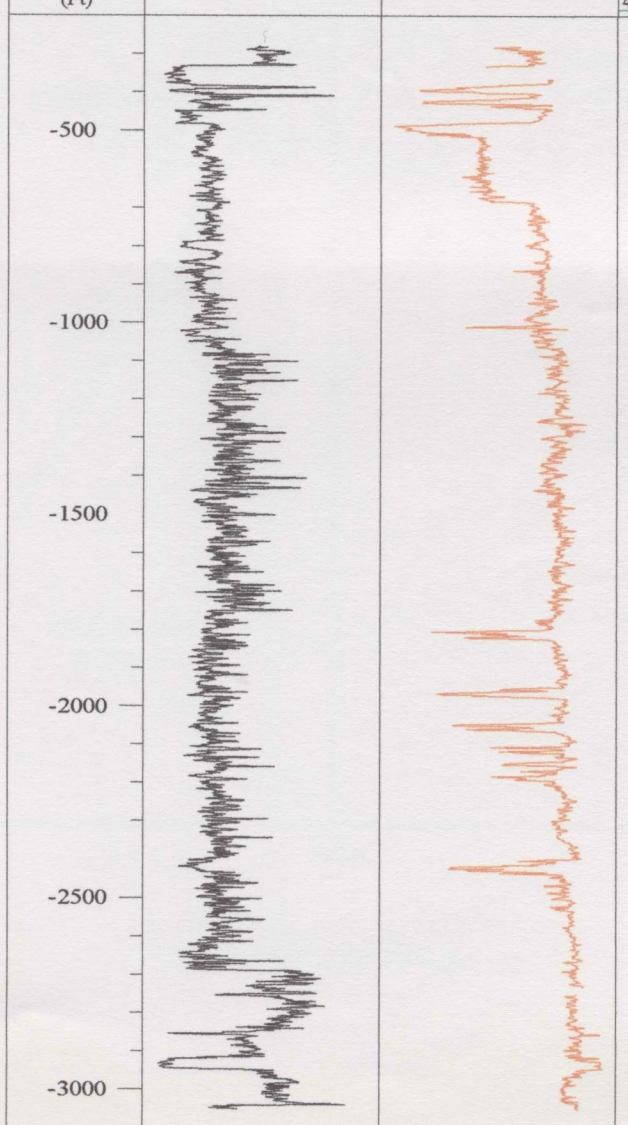
Prees-1 Scale: 1:6000



Lithostratigraphy

Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			6480.0	1975.00
Sherwood Sandstone 945.00m	Helsby Sdst 225.00m	? Frodsham Sdst 110.00m	6840.5	2085.00
		? Delamere Sdst 115.00m	7218.0	2200.00
	Wilmslow Sdst 230.00m		7972.4	2430.00
	Chester Pebble Beds 490.00m		9580.0	2920.00
Cumbrian Coast 160.00m	Kinnerton Sdst 100.00m		9908.0	3020.00
	Manchester Marl 60.00m		10104.9	3080.00
Appleby 520.00m	Collyhurst Sdst 520.00m		11811.0	3600.00
Carb.				

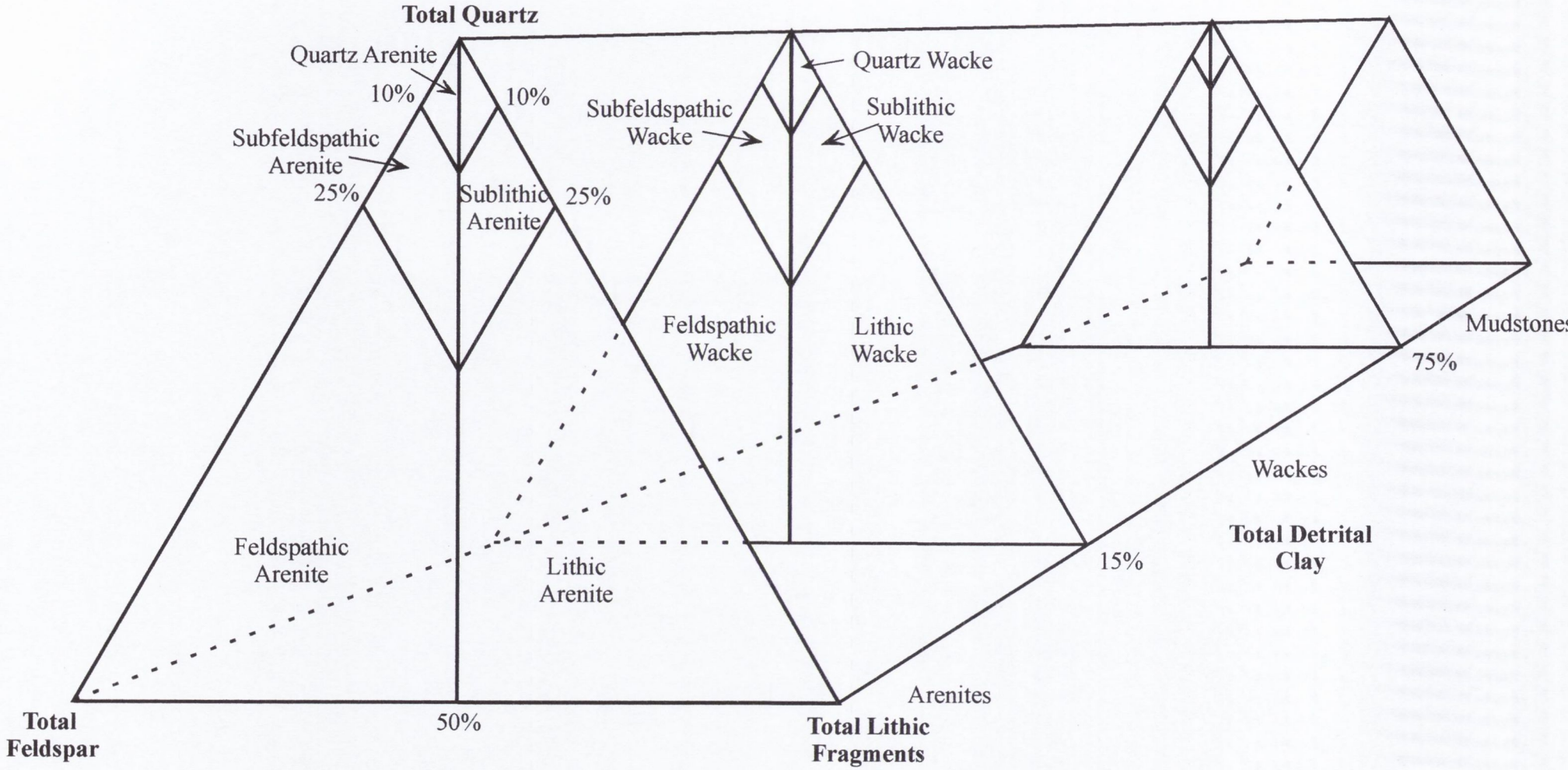
Thistleton-1 Scale: 1:6000



Lithostratigraphy				
Group	Formation	Member	Depth (Ft)	Depth (m)
Mercia Mdst			330.0	100.60
Sherwood Sandstone 718.40m	Ormskirk Sdst 224.00m	? OS2b 50.29m	480.0	146.30
		? OS2a 93.60m	787.0	239.90
		? OS1 84.70m	1065.0	324.60
	St Bees Sdst 494.40m	? Calder 494.40m	2687.0	819.00
Cumbrian Coast 106.10m	Barrowmouth Mdst 70.70m		2919.0	889.70
	St Bees Evaporites 35.40m		3035.0	925.10
Carb.				

APPENDIX III

Modal Analysis Data



Lithological subdivisions determined from petrographic data (modified from Dott 1964).

Well 110/2-6						
Sample	**941.85**	**944.25**	**944.85**	**945.50**	**947.85**	**950.95**
Stratigraphy	OS2b	OS2b	OS2b	OS2b	OS2b	OS2b
Facies	DSF	HSB	HSB	HSB	LSB	WSF
Lithology	SFA	SFA	SFA	dSFA	dLA	SFA
Detrital Mineralogy						
Total Quartz	47.50	44.50	52.00	49.00	37.50	43.50
Monocrystalline	30.00	24.00	31.50	28.00	17.00	33.50
Polycrystalline Equant	11.00	14.50	15.50	14.00	15.00	6.00
Polycrystalline Schistose	2.50	1.50	3.50	3.50	3.00	0.50
Chert	4.00	4.50	1.50	3.50	2.50	3.50
Total Feldspar	16.50	16.00	13.50	14.50	7.00	12.00
K-Feldspar	14.50	15.00	13.00	13.50	6.00	11.00
Plagioclase	2.00	1.00	0.50	1.00	1.00	1.00
Total Mica	0.50	0.50	tr		0.50	1.50
Muscovite	0.50	0.50	tr		0.50	1.00
Biotite		tr				0.50
Chlorite		tr				
Total Rock Fragments	7.50	8.50	9.00	7.00	28.00	3.50
Granitic	2.50	3.50	3.00	4.00	1.50	1.00
Volcanic	0.50		tr	tr		
Metamorphic	3.50	4.50	4.50	2.00	3.00	2.00
Sedimentary			1.50	1.00	23.50	0.50
Caliche	1.00	0.50				
Detrital Opaques	tr	tr				tr
Heavy Minerals	tr	tr	tr	tr		tr
Organics						
Non-Resolvable Clays	4.50	9.50	7.00	6.50	1.00	12.00
Authigenic Mineralogy						
Total Blocky Cements	13.00	12.50	2.50	15.50	20.00	13.50
Non-Ferroan Calcite	0.50					
Ferroan Calcite						
Non-Ferroan Dolomite	9.00	8.00	1.00	11.00	10.50	6.00
Ferroan Dolomite		1.50	tr	2.00	2.50	2.50
Gypsum/Anhydrite	0.5		tr		2.50	
Quartz	3.50	3.00	1.50	2.50	4.50	4.00
K-feldspar	tr					0.50
Plagioclase						
Pyrite	tr					
Haematite			tr			0.50
Anatase		tr		tr		tr
Total Clay Cements	6.50	6.00	6.50	6.50	3.50	13.50
Illite	6.00	5.00	6.50	5.00	3.50	8.50
Kaolinite	0.50	1.00		1.00	tr	5.00
Chlorite				0.50		tr
Total Porosity	3.50	2.50	9.50	1.00	2.50	0.50
Primary	3.00	2.50	6.00	0.50	1.50	0.50
Secondary	0.50	tr	3.50	0.50	1.00	tr
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00
% Total Quartz	65.97	64.03	69.80	69.50	51.37	71.90
% Total Feldspar	22.92	23.02	18.12	20.57	9.59	19.83
% Total Lithics	11.11	12.95	12.08	9.93	39.04	8.26

Lithological qualifyers

Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers

Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

Well 110/2-6						
Sample	**953.72**	**956.15**	**957.95**	**961.35**	**964.65**	**965.85**
Stratigraphy	OS2b	OS2b	OS2b	OS2b	OS2b	OS2b
Facies	DSF	AED	AED	SFL	AED	AED
Lithology	dSFA	SFA	dSFA	dSLA	SLA	SLA
Detrital Mineralogy						
Total Quartz	51.50	42.50	44.00	41.50	43.00	42.50
Monocrystalline	35.50	19.50	26.00	21.00	23.00	19.50
Polycrystalline Equant	12.00	16.50	12.50	14.50	12.50	14.00
Polycrystalline Schistose	3.00	3.50	3.00	2.00	4.50	4.50
Chert	1.00	3.00	2.50	4.00	3.00	4.50
Total Feldspar	10.00	10.50	10.50	11.50	10.50	11.50
K-Feldspar	8.50	8.50	9.00	9.00	9.00	8.00
Plagioclase	1.50	2.00	1.50	2.50	1.50	3.50
Total Mica		tr	2.00	1.00	0.50	tr
Muscovite		tr	1.00	0.50	0.50	tr
Biotite			0.50	0.50		
Chlorite			0.50			
Total Rock Fragments	8.00	7.00	7.50	10.50	11.50	13.00
Granitic	3.50	5.00	4.50	2.50	5.50	6.50
Volcanic		0.50		0.50	1.00	1.50
Metamorphic	4.00	1.50	3.00	3.00	5.00	5.00
Sedimentary	0.50			4.50		
Caliche			tr			
Detrital Opaques	tr		tr	0.50		
Heavy Minerals	tr		tr	tr	0.50	tr
Organics						
Non-Resolvable Clays	3.00	6.50	6.00	7.00	5.50	3.00
Authigenic Mineralogy						
Total Blocky Cements	13.50	11.50	16.00	14.50	7.00	8.50
Non-Ferroan Calcite						
Ferroan Calcite						
Non-Ferroan Dolomite	8.50	8.00	9.50	7.50	0.50	2.00
Ferroan Dolomite	1.50	0.50	2.00	5.00	1.00	2.50
Gypsum/Anhydrite					0.50	
Quartz	3.50	3.00	4.00	2.00	4.50	4.00
K-feldspar			0.50		0.50	
Plagioclase						
Pyrite			tr			
Haematite						
Anatase	tr	tr				tr
Total Clay Cements	10.00	9.00	7.00	11.50	8.00	6.50
Illite	5.50	5.00	3.00	9.50	6.50	5.50
Kaolinite	4.50	4.00	4.00	2.00	1.50	1.00
Chlorite						
Total Porosity	4.00	13.00	7.00	2.00	13.50	15.00
Primary	3.00	11.50	5.00	2.00	12.00	10.50
Secondary	1.00	1.50	2.00	tr	1.50	4.50
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00
% Total Quartz	74.10	70.83	68.75	63.85	65.15	63.43
% Total Feldspar	14.39	17.50	16.41	17.69	15.91	17.17
% Total Lithics	11.51	11.67	14.84	18.46	18.94	19.40

Lithological qualifyers

Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers	
Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

Well 110/2-6						
Sample	**967.90**	**970.90**	**974.00**	**977.90**	**981.50**	**984.55**
Stratigraphy	OS2b	OS2b	OS2b	OS2b	OS2b	OS2b
Facies	PAB	LSB	HSB	HSB	WSF	LSB
Lithology	SFA	SLA	SLA	QA	idSLA	SLA
Detrital Mineralogy						
Total Quartz	44.00	43.50	53.50	64.00	43.00	52.50
Monocrystalline	21.00	25.50	35.00	38.50	36.50	31.00
Polycrystalline Equant	14.50	11.50	11.50	18.00	5.00	17.50
Polycrystalline Schistose	5.00	4.00	4.50	4.50	0.50	1.50
Chert	3.50	2.50	2.50	3.00	1.00	2.50
Total Feldspar	12.00	10.50	4.50	5.50	3.00	3.00
K-Feldspar	9.50	8.50	4.00	4.50	2.50	3.00
Plagioclase	2.50	2.00	0.50	1.00	0.50	tr
Total Mica	2.50	1.00	0.50	0.00	3.50	tr
Muscovite	2.50	1.00	tr		3.00	tr
Biotite	tr		0.50		0.50	tr
Chlorite						
Total Rock Fragments	8.50	10.00	6.50	7.00	3.50	13.50
Granitic	4.00	4.50	3.50	2.00	1.50	5.50
Volcanic	tr	0.50				
Metamorphic	4.50	4.50	3.00	4.50	2.00	7.00
Sedimentary		0.50	tr	0.50		1.00
Caliche			tr			
Detrital Opaques	tr	tr		tr	tr	tr
Heavy Minerals	0.50	0.50	tr	tr	tr	tr
Organics						
Non-Resolvable Clays	3.50	4.00	2.00	4.00	2.50	7.00
Authigenic Mineralogy						
Total Blocky Cements	13.50	14.50	17.00	11.00	16.00	13.00
Non-Ferroan Calcite						
Ferroan Calcite						
Non-Ferroan Dolomite	4.50	4.00	7.00	1.00	8.00	2.50
Ferroan Dolomite	3.50	3.00	1.50	2.00	4.00	2.50
Gypsum/Anhydrite	tr	tr	tr	tr	0.50	tr
Quartz	5.00	7.00	8.50	7.50	3.50	8.00
K-feldspar	0.50			0.50		
Plagioclase						
Pyrite						
Haematite						tr
Anatase	tr	0.50	tr		tr	tr
Total Clay Cements	8.50	7.50	4.50	5.00	21.50	7.50
Illite	5.50	6.00	2.00	1.50	16.00	3.50
Kaolinite	3.00	1.50	2.50	3.50	5.00	4.00
Chlorite					0.50	
Total Porosity	7.00	8.50	5.50	3.50	7.00	3.50
Primary	5.50	5.00	5.00	2.50	5.00	3.00
Secondary	1.50	3.50	0.50	1.00	2.00	0.50
TOTAL	100.00	100.00	94.00	100.00	100.00	100.00
% Total Quartz	65.19	66.41	82.31	83.66	81.13	76.09
% Total Feldspar	17.78	16.03	6.92	7.19	5.66	4.35
% Total Lithics	17.03	17.56	10.77	9.15	13.21	19.56

Lithological qualifyers	
Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW
Sub-qualifyers	
Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

Well 110/2-6						
Sample	**988.70**	**991.45**	**994.85**	**998.50**	**1000.30**	**1002.15**
Stratigraphy	OS2b	OS2b	OS2b	OS2b	OS2b	OS2b
Facies	HSB	CPB	LSB	ASS	SFL	FPL
Lithology	SLA	sSLA	SLA	SLA	QA	idQW
Detrital Mineralogy						
Total Quartz	55.50	56.00	54.50	58.00	59.00	34.50
Monocrystalline	34.50	31.50	35.50	33.00	38.50	21.00
Polycrystalline Equant	17.50	18.50	15.00	19.50	15.50	8.50
Polycrystalline Schistose	3.00	3.00	1.00	2.50	2.00	2.00
Chert	0.50	3.00	3.00	3.00	3.00	3.00
Total Feldspar	2.00	1.50	2.00	tr	1.00	1.00
K-Feldspar	2.00	1.50	2.00	tr	1.00	1.00
Plagioclase	tr					
Total Mica	0.50	1.50	tr	tr	tr	0.50
Muscovite	0.50	1.50	tr	tr	tr	tr
Biotite	tr	tr		tr	tr	tr
Chlorite						0.50
Total Rock Fragments	14.00	12.50	11.50	8.00	5.50	1.00
Granitic	4.00	2.00	3.50	3.00	3.50	0.50
Volcanic		tr		tr		
Metamorphic	5.50	5.00	4.00	5.00	1.00	tr
Sedimentary	4.50	5.50	4.00		1.00	0.50
Caliche						tr
Detrital Opaques	tr	tr	tr		tr	0.50
Heavy Minerals	tr	tr	tr	tr	tr	1.00
Organics						
Non-Resolvable Clays	2.00	4.00	1.00	2.00	2.50	30.00
Authigenic Mineralogy						
Total Blocky Cements	17.50	13.00	24.50	11.50	7.50	15.00
Non-Ferroan Calcite						
Ferroan Calcite						
Non-Ferroan Dolomite	6.00	1.50	13.50	3.00	2.00	13.00
Ferroan Dolomite	1.50	0.50	3.00	1.00	2.00	1.50
Gypsum/Anhydrite	0.50	tr	1.00		0.50	
Quartz	9.00	11.00	7.00	7.00	3.00	
K-feldspar						
Plagioclase						
Pyrite						
Haematite						
Anatase	0.50	tr	tr	0.50	tr	0.50
Total Clay Cements	5.50	8.50	2.50	10.00	11.00	15.50
Illite	2.50	6.00	0.50	4.00	9.00	15.00
Kaolinite	3.00	2.50	2.00	6.00	2.00	0.50
Chlorite						
Total Porosity	3.00	3.00	4.00	10.50	13.50	1.00
Primary	2.50	1.50	3.50	8.00	9.50	
Secondary	0.50	1.50	0.50	2.50	4.00	1.00
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00
% Total Quartz	77.08	78.32	80.15	87.88	90.08	89.61
% Total Feldspar	2.78	2.10	2.94	0.00	1.53	2.60
% Total Lithics	20.14	19.58	16.91	12.12	8.39	7.79

Lithological qualifyers

Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers

Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

Well 110/2-6						
Sample	**1008.20**	**1012.10**	**1015.00**	**1017.40**	**1024.05**	**1027.35**
Stratigraphy	OS2b	OS2b	OS2b	OS2b	OS2b	OS2b
Facies	HSB	LSB	SFL	AED	CPB	LSB
Lithology	dQA	dLA	QA	SLA	QA	iSLA
Detrital Mineralogy						
Total Quartz	59.50	44.00	59.00	57.50	67.00	51.50
Monocrystalline	31.00	26.00	35.50	35.00	37.50	26.00
Polycrystalline Equant	21.00	13.00	18.50	17.00	19.50	20.00
Polycrystalline Schistose	6.50	4.00	3.00	5.00	10.00	2.00
Chert	1.00	1.00	2.00	0.50		3.50
Total Feldspar	1.50	0.50	1.00	1.00	1.50	1.50
K-Feldspar	1.50	0.50	1.00	1.00	1.00	1.00
Plagioclase				tr	0.50	0.50
Total Mica	tr	0.50	tr	tr	0.00	1.00
Muscovite	tr	0.50	tr	tr		0.50
Biotite	tr					0.50
Chlorite						
Total Rock Fragments	5.50	20.00	4.50	9.50	6.00	10.50
Granitic	3.00	3.50	2.50	7.00	3.50	4.50
Volcanic						
Metamorphic	2.50	2.50	2.00	2.50	2.50	4.50
Sedimentary		14.00		tr		1.50
Caliche						
Detrital Opaques	tr		tr	tr	tr	tr
Heavy Minerals	tr	tr	tr	tr	tr	1.00
Organics						
Non-Resolvable Clays	0.50	1.00	9.00	4.50	3.00	5.50
Authigenic Mineralogy						
Total Blocky Cements	27.50	30.00	5.00	4.00	14.50	8.50
Non-Ferroan Calcite						
Ferroan Calcite						
Non-Ferroan Dolomite	20.50	22.50	2.50		2.00	0.50
Ferroan Dolomite	1.00	4.50	tr	tr	0.50	1.00
Gypsum/Anhydrite	0.50	0.50	tr		3.5	0.50
Quartz	5.50	2.50	2.50	4.00	8.00	6.50
K-feldspar					0.50	
Plagioclase						
Pyrite						tr
Haematite				tr		tr
Anatase	tr	tr	tr	tr		tr
Total Clay Cements	3.00	2.50	10.00	12.00	1.50	16.50
Illite	1.50	2.50	6.50	9.00	1.50	12.00
Kaolinite	1.50		3.50	3.00	tr	4.50
Chlorite						
Total Porosity	2.50	1.50	11.50	11.50	6.50	4.00
Primary	2.00	0.50	9.50	11.00	6.00	2.00
Secondary	0.50	1.00	2.00	0.50	0.50	2.00
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00
% Total Quartz	89.47	67.69	91.47	84.56	89.93	78.63
% Total Feldspar	2.26	0.77	1.55	1.47	2.01	2.29
% Total Lithics	8.27	31.54	6.98	13.97	8.06	19.08

Lithological qualifyers

Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers	
Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

Well 110/2-6						
Sample	**1030.40**	**1033.20**	**1036.65**	**1040.25**	**1043.10**	**1043.20**
Stratigraphy	OS2b	OS2b	OS2b	OS2b	OS2b	OS2b
Facies	LSB	HSB	HSB	LSB	HSB	HSB
Lithology	LA	SLA	SLA	iSLA	iSLA	iSLA
Detrital Mineralogy						
Total Quartz	50.00	51.00	58.00	51.50	55.00	51.50
Monocrystalline	26.00	27.50	30.00	30.00	35.50	29.50
Polycrystalline Equant	16.50	16.50	20.00	13.50	10.50	17.50
Polycrystalline Schistose	6.00	3.00	5.00	4.00	7.50	2.50
Chert	1.50	4.00	3.00	4.00	1.50	2.00
Total Feldspar	1.50	3.00	2.50	1.00	2.00	2.00
K-Feldspar	tr	0.50	1.00	1.00	0.50	0.50
Plagioclase	1.50	2.50	1.50	tr	1.50	1.50
Total Mica	2.00	2.00	2.00	tr	tr	4.00
Muscovite	2.00	1.50	2.00	tr	tr	4.00
Biotite	tr	0.50	tr		tr	tr
Chlorite			tr			
Total Rock Fragments	17.50	14.50	12.50	11.00	8.00	11.50
Granitic	6.50	3.50	7.00	6.00	5.00	4.00
Volcanic	tr	0.50		0.50	0.50	
Metamorphic	6.50	7.50	4.00	3.50	2.00	4.50
Sedimentary	4.50	3.00	1.50	1.00	0.50	3.00
Caliche						
Detrital Opaques	tr	tr	tr			tr
Heavy Minerals	0.50	tr	tr	tr	tr	1.00
Organics						
Non-Resolvable Clays	2.00	4.50	1.00	2.00	3.50	3.50
Authigenic Mineralogy						
Total Blocky Cements	11.50	9.50	12.00	10.50	12.50	6.00
Non-Ferroan Calcite						
Ferroan Calcite						
Non-Ferroan Dolomite	5.00	1.00	4.00	2.00	2.50	
Ferroan Dolomite	0.50	0.50	1.00	1.00	3.00	
Gypsum/Anhydrite	tr	1.00				
Quartz	5.50	6.50	6.50	7.50	7.00	5.00
K-feldspar						
Plagioclase						
Pyrite						
Haematite	0.50	tr	tr		tr	1.00
Anatase	tr	0.50	0.50		tr	tr
Total Clay Cements	10.00	10.00	10.00	13.00	13.00	13.00
Illite	8.00	6.50	8.50	11.50	11.00	11.50
Kaolinite	2.00	3.50	1.50	1.50	2.00	1.50
Chlorite						
Total Porosity	5.00	5.50	2.00	11.00	6.00	7.50
Primary	3.50	3.00	0.50	7.50	3.00	3.50
Secondary	1.50	2.50	1.50	3.50	3.00	4.00
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00
% Total Quartz	69.93	72.34	77.34	81.10	84.61	73.57
% Total Feldspar	2.10	4.26	3.33	1.58	3.08	2.86
% Total Lithics	27.97	23.40	19.33	17.32	12.31	23.57

Lithological qualifyers	
Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW
Sub-qualifyers	
Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

Well 110/2-6						
Sample	**1043.30**	**1053.05**	**1056.20**	**1059.50**	**1062.25**	**1065.90**
Stratigraphy	OS2b	OS2b	OS2b	OS2a	OS2a	OS2a
Facies	HSB	PAB	HSB	DSF	DSF	HSB
Lithology	sSLA	sSLA	QA	SLA	iSLA	QA
Detrital Mineralogy						
Total Quartz	59.00	59.00	67.50	49.00	62.00	73.00
Monocrystalline	39.50	33.00	39.50	30.50	44.00	46.00
Polycrystalline Equant	14.50	19.00	22.50	15.00	15.50	16.50
Polycrystalline Schistose	3.50	6.00	4.00	3.00	1.50	8.00
Chert	1.50	1.00	1.50	0.50	1.00	2.50
Total Feldspar	2.00	0.50	0.50	4.00	2.50	2.50
K-Feldspar	1.00	0.50	0.50	3.50	2.00	2.00
Plagioclase	1.00			0.50	0.50	0.50
Total Mica	tr	0.00	tr	tr	1.00	tr
Muscovite	tr		tr	tr	1.00	tr
Biotite					tr	
Chlorite						
Total Rock Fragments	8.00	13.50	6.00	12.00	3.00	1.50
Granitic	1.00	5.00	1.00	8.50	1.00	
Volcanic	0.50	0.50				tr
Metamorphic	4.50	2.50	4.50	2.50	2.00	1.50
Sedimentary	2.00	5.50	0.50	1.00		
Caliche						
Detrital Opaques	tr	tr	tr	tr	tr	
Heavy Minerals	tr	tr	tr	0.50	0.50	tr
Organics					tr	
Non-Resolvable Clays	1.00	0.50	tr	1.50	5.50	2.50
Authigenic Mineralogy						
Total Blocky Cements	15.50	14.50	11.50	13.00	3.50	10.50
Non-Ferroan Calcite						
Ferroan Calcite						
Non-Ferroan Dolomite	2.00	3.50	2.00	8.50	1.00	4.50
Ferroan Dolomite	1.00	tr	tr	0.50	tr	0.50
Gypsum/Anhydrite						
Quartz	12.50	11.00	9.50	4.00	2.50	5.50
K-feldspar						
Plagioclase						
Pyrite					tr	
Haematite	tr			tr		
Anatase	tr		tr	tr	tr	
Total Clay Cements	5.50	4.50	5.00	9.50	11.00	5.00
Illite	5.50	4.50	5.00	9.50	10.50	4.50
Kaolinite					0.50	0.50
Chlorite						
Total Porosity	9.00	7.50	9.50	10.50	11.00	5.00
Primary	6.00	6.00	5.50	9.50	10.50	3.50
Secondary	3.00	1.50	4.00	1.00	0.50	1.50
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00
% Total Quartz	85.51	80.82	91.22	74.81	89.86	94.80
% Total Feldspar	2.90	0.69	0.67	6.11	3.62	3.25
% Total Lithics	11.59	18.49	8.11	19.08	6.52	1.95

Lithological qualifyers	
Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW
Sub-qualifyers	
Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

Well 110/2-6						
Sample	**1068.80**	**1073.30**	**1077.70**	**1080.15**	**1086.95**	**1090.40**
Stratigraphy	OS2a	OS2a	OS2a	OS2a	OS2a	OS2a
Facies	DSF	DSF	ASS	DSF	DSF	DRS
Lithology	QA	SFA	dQA	SLA	QA	QA
Detrital Mineralogy						
Total Quartz	67.00	55.50	61.00	56.50	60.00	63.50
Monocrystalline	40.50	39.50	43.00	40.50	40.50	43.50
Polycrystalline Equant	19.50	11.00	12.50	14.00	18.50	16.00
Polycrystalline Schistose	5.00	2.50	5.00	1.00		2.50
Chert	2.00	2.50	0.50	1.00	1.00	1.50
Total Feldspar	7.00	8.50	3.00	8.00	5.50	3.50
K-Feldspar	5.50	7.50	3.00	7.50	5.00	2.50
Plagioclase	1.50	1.00		0.50	0.50	1.00
Total Mica	tr	1.00	tr	1.50	0.50	0.50
Muscovite	tr	1.00	tr	1.50	0.50	0.50
Biotite		tr	tr	tr	tr	
Chlorite				tr	tr	
Total Rock Fragments	5.00	6.00	7.00	7.50	5.50	4.00
Granitic	1.00	2.50	2.50	5.00	2.50	2.00
Volcanic	tr	tr		0.50		
Metamorphic	4.00	3.50	4.50	2.00	3.00	2.00
Sedimentary	tr	tr				
Caliche						
Detrital Opaques	tr	tr			tr	tr
Heavy Minerals	tr	tr	tr	tr	tr	tr
Organics						
Non-Resolvable Clays	1.50	1.50	tr	3.00	1.50	2.00
Authigenic Mineralogy						
Total Blocky Cements	4.00	5.00	24.00	8.00	6.50	10.00
Non-Ferroan Calcite	tr					
Ferroan Calcite						
Non-Ferroan Dolomite	1.00	0.50	19.00	3.00	4.00	4.00
Ferroan Dolomite		1.00	2.00	1.00	1.00	1.00
Gypsum/Anhydrite	tr	tr	tr			
Quartz	3.00	3.00	3.00	4.00	1.50	5.00
K-feldspar						
Plagioclase						
Pyrite						
Haematite			tr		tr	
Anatase		0.50	tr	tr	tr	tr
Total Clay Cements	4.50	6.00	2.50	8.00	8.00	9.50
Illite	4.50	5.50	2.50	6.00	7.00	9.50
Kaolinite	tr	0.50		2.00	1.00	tr
Chlorite						
Total Porosity	11.00	16.50	2.50	7.50	12.50	7.00
Primary	7.00	13.00	2.00	2.50	9.00	4.00
Secondary	4.00	3.50	0.50	5.00	3.50	3.00
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00
% Total Quartz	84.81	78.17	85.92	76.87	83.92	88.81
% Total Feldspar	8.86	11.97	4.22	10.88	7.69	4.90
% Total Lithics	6.33	9.86	9.86	12.25	8.39	6.29

Lithological qualifyers

Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers	
Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

Well 110/2-6						
Sample	**1093.70**	**1097.65**	**1101.05**	**1105.60**	**1108.15**	**1111.20**
Stratigraphy	OS2a	OS2a	OS2a	OS1	OS1	OS1
Facies	AED	AED	DSF	HSB	DSF	ASS
Lithology	QA	QA	dSLA	sQA	QA	SFA
Detrital Mineralogy						
Total Quartz	74.50	66.50	55.00	66.00	60.00	60.50
Monocrystalline	46.50	44.00	37.50	45.50	38.00	39.50
Polycrystalline Equant	23.00	18.00	14.50	14.50	16.50	19.00
Polycrystalline Schistose	3.50	1.50	1.50	5.00	5.50	1.50
Chert	1.50	3.00	1.50	1.00	tr	0.50
Total Feldspar	tr	2.00	6.00	4.50	4.50	9.00
K-Feldspar	tr	2.00	5.00	3.00	4.00	7.50
Plagioclase		tr	1.00	1.50	0.50	1.50
Total Mica	0.50	tr	0.50	0.50	1.00	0.50
Muscovite	0.50	tr	tr	0.50	1.00	0.50
Biotite		tr	0.50			tr
Chlorite	tr					
Total Rock Fragments	7.00	5.00	6.50	2.50	5.50	7.50
Granitic	2.00	3.50	6.50	2.50	4.00	6.50
Volcanic		tr				
Metamorphic	5.00	1.00	tr	tr	1.50	1.00
Sedimentary						
Caliche		0.50	tr			
Detrital Opaques		tr	tr			tr
Heavy Minerals	tr	tr	tr	tr	0.50	0.50
Organics						
Non-Resolvable Clays	1.00	2.00	1.00	1.50	2.00	0.50
Authigenic Mineralogy						
Total Blocky Cements	4.50	3.50	11.50	11.50	7.00	9.00
Non-Ferroan Calcite						
Ferroan Calcite						
Non-Ferroan Dolomite	2.00	1.00	10.00	0.50	1.50	5.00
Ferroan Dolomite	0.50	1.00	0.50	0.50	0.50	
Gypsum/Anhydrite		tr	tr			
Quartz	2.00	1.50	1.00	10.50	5.00	4.00
K-feldspar						
Plagioclase						
Pyrite						
Haematite	tr			tr	tr	
Anatase	tr	tr	tr	tr	tr	tr
Total Clay Cements	6.00	9.00	5.50	6.50	9.50	4.50
Illite	5.50	8.50	5.50	6.50	8.00	3.00
Kaolinite	0.50	0.50	tr		1.50	1.50
Chlorite						
Total Porosity	6.50	12.00	14.00	7.00	10.00	8.00
Primary	4.50	10.50	10.00	3.00	8.50	4.50
Secondary	2.00	1.50	4.00	4.00	1.50	3.50
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00
% Total Quartz	90.85	90.48	80.88	89.80	83.92	77.56
% Total Feldspar	0.00	2.72	8.82	6.12	6.29	11.54
% Total Lithics	9.15	6.80	10.30	4.08	9.79	10.90

Lithological qualifyers

Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers

Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

Well 110/2-6						
Sample	**1114.40**	**1123.00**	**1124.15**	**1125.95**	**1129.20**	**1130.25**
Stratigraphy	OS1	OS1	OS1	OS1	OS1	OS1
Facies	HSB	AED	ASS	HSB	HSB	HSB
Lithology	sSLA	SLA	SFA	dSLA	SLA	SFA
Detrital Mineralogy						
Total Quartz	60.50	58.00	62.50	43.50	57.00	53.50
Monocrystalline	36.00	33.50	39.50	28.00	35.50	31.00
Polycrystalline Equant	18.00	18.50	17.00	13.50	17.50	18.50
Polycrystalline Schistose	5.00	3.50	4.50	1.50	2.50	3.50
Chert	1.50	2.50	1.50	0.50	1.50	0.50
Total Feldspar	9.00	7.50	9.00	5.00	6.50	10.50
K-Feldspar	8.00	6.50	7.50	5.00	5.50	10.00
Plagioclase	1.00	1.00	1.50		1.00	0.50
Total Mica	1.00	tr	0.50	0.50	0.50	tr
Muscovite	1.00	tr	0.50	0.50	0.50	
Biotite	tr					tr
Chlorite						
Total Rock Fragments	11.00	8.00	6.00	6.00	10.00	7.50
Granitic	7.50	3.00	3.50	2.50	5.00	5.50
Volcanic					tr	tr
Metamorphic	2.50	5.00	2.50	3.50	4.00	1.50
Sedimentary	1.00		tr		0.50	0.50
Caliche		tr	tr		0.50	
Detrital Opaques	tr		tr	tr		
Heavy Minerals	tr	tr	tr	tr	tr	tr
Organics						
Non-Resolvable Clays	tr	1.50	2.00	tr	2.00	2.00
Authigenic Mineralogy						
Total Blocky Cements	11.00	2.00	2.00	34.50	7.50	9.50
Non-Ferroan Calcite						
Ferroan Calcite						
Non-Ferroan Dolomite	0.50	1.00	0.50	32.00	0.50	1.00
Ferroan Dolomite		tr		1.50	0.50	tr
Gypsum/Anhydrite					tr	
Quartz	10.50	1.00	1.50	1.00	6.50	8.50
K-feldspar	tr	tr			tr	tr
Plagioclase						
Pyrite						
Haematite		tr		tr		
Anatase			tr			
Total Clay Cements	5.00	7.50	7.00	4.00	5.00	7.50
Illite	4.50	7.50	6.00	3.50	5.00	7.00
Kaolinite	0.50	tr	1.00	0.50	tr	0.50
Chlorite						
Total Porosity	2.50	15.50	11.00	6.50	11.50	9.50
Primary	1.00	12.00	9.00	6.00	7.50	7.00
Secondary	1.50	3.50	2.00	0.50	4.00	2.50
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00
% Total Quartz	74.23	78.91	80.13	79.09	77.03	74.83
% Total Feldspar	11.04	10.20	11.54	9.09	8.78	14.68
% Total Lithics	14.73	10.89	8.33	11.82	14.19	10.49

Lithological qualifyers	
Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW
Sub-qualifyers	
Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

Well 110/2-6						
Sample	**1134.45**	**1137.50**	**1144.30**	**1150.80**	**1153.95**	**1157.05**
Stratigraphy	OS1	OS1	OS1	OS1	OS1	OS1
Facies	IBC	AED	AED	ASS	AED	AED
Lithology	sSLFA	SFA	SFA	dSFA	SFA	SFA
Detrital Mineralogy						
Total Quartz	55.00	51.00	44.50	50.00	57.00	58.50
Monocrystalline	27.50	32.00	27.00	37.50	39.00	39.50
Polycrystalline Equant	17.50	12.50	12.50	10.00	13.50	14.00
Polycrystalline Schistose	8.50	3.50	4.00	2.00	2.50	4.50
Chert	1.50	3.00	1.00	0.50	2.00	0.50
Total Feldspar	8.50	12.00	14.00	11.50	8.50	10.50
K-Feldspar	8.00	11.50	12.00	10.00	7.50	8.50
Plagioclase	0.50	0.50	2.00	1.50	1.00	2.00
Total Mica		tr	0.50	1.50	0.50	0.50
Muscovite		tr	0.50	1.50	0.50	0.50
Biotite			tr	tr		
Chlorite				tr	tr	
Total Rock Fragments	8.50	6.00	12.00	3.50	7.50	9.50
Granitic	4.50	3.50	4.50	2.00	5.00	4.50
Volcanic	tr			0.50		
Metamorphic	4.00	2.50	7.50	1.00	2.50	5.00
Sedimentary	tr		tr			
Caliche		tr	tr			
Detrital Opaques		tr	tr	tr	tr	tr
Heavy Minerals	tr	tr	tr	tr	tr	tr
Organics			tr		tr	
Non-Resolvable Clays	1.00	1.00	2.00	3.00		2.00
Authigenic Mineralogy						
Total Blocky Cements	11.50	4.50	3.00	13.50	9.50	1.50
Non-Ferroan Calcite						
Ferroan Calcite						
Non-Ferroan Dolomite	0.50	0.50	tr	12.00	4.00	tr
Ferroan Dolomite	tr	tr		tr	1.00	tr
Gypsum/Anhydrite						
Quartz	11.00	3.50	3.00	1.50	4.00	1.50
K-feldspar	tr	0.50	tr	tr	tr	
Plagioclase						
Pyrite					tr	
Haematite						
Anatase			tr	tr	0.50	
Total Clay Cements	3.00	9.00	5.50	7.50	3.00	6.00
Illite	2.50	8.00	4.50	7.00	3.00	6.00
Kaolinite	0.50	1.00	1.00	0.50		
Chlorite						
Total Porosity	12.50	16.50	18.50	9.50	14.00	11.50
Primary	8.50	8.50	12.00	6.50	10.00	8.50
Secondary	4.00	8.00	6.50	3.00	4.00	3.00
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00
% Total Quartz	76.38	73.91	62.68	75.19	77.55	74.05
% Total Feldspar	11.81	17.39	19.72	17.29	11.56	13.29
% Total Lithics	11.81	8.70	17.60	7.52	10.89	12.66

Lithological qualifyers	
Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers	
Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

Well 110/2-6						
Sample	**1161.90**	**1167.10**	**1170.10**	**1177.20**	**1180.65**	**1187.00**
Stratigraphy	OS1	OS1	OS1	OS1	OS1	CSM
Facies	SFL	LSB	DRS	DSF	LSB	CPB
Lithology	dSLA	SFA	SLA	SFA	sSLA	sSLA
Detrital Mineralogy						
Total Quartz	52.00	60.50	51.00	52.00	63.00	56.00
Monocrystalline	35.00	39.50	31.50	35.00	41.00	36.50
Polycrystalline Equant	11.00	17.50	15.00	14.00	10.50	12.00
Polycrystalline Schistose	3.50	2.50	2.50	3.00	8.00	4.00
Chert	2.50	1.00	2.00	tr	3.50	3.50
Total Feldspar	9.00	10.50	9.00	10.00	5.00	5.00
K-Feldspar	9.00	9.00	8.50	8.50	5.00	3.50
Plagioclase		1.50	0.50	1.50	tr	1.50
Total Mica		1.00		tr		tr
Muscovite		1.00		tr		tr
Biotite				tr		tr
Chlorite						
Total Rock Fragments	10.50	5.50	9.50	9.50	9.00	12.00
Granitic	7.00	2.50	5.00	5.50	5.50	5.00
Volcanic	1.00	tr				
Metamorphic	2.50	3.00	4.50	4.00	3.50	7.00
Sedimentary						
Caliche			tr			
Detrital Opaques	tr	tr	tr	tr		
Heavy Minerals	0.50	tr	tr	tr	tr	tr
Organics		tr			tr	
Non-Resolvable Clays	0.50	1.50	0.50	3.50	1.00	2.00
Authigenic Mineralogy						
Total Blocky Cements	23.00	6.50	6.00	7.00	19.50	14.00
Non-Ferroan Calcite						
Ferroan Calcite						
Non-Ferroan Dolomite	20.00	2.00	1.00	3.00	6.50	1.50
Ferroan Dolomite	1.50	0.50	0.50	0.50		tr
Gypsum/Anhydrite						
Quartz	1.50	4.00	4.00	3.00	13.00	10.50
K-feldspar			0.50		tr	
Plagioclase						
Pyrite			tr	0.50		tr
Haematite		tr	tr	tr		2.00
Anatase		tr		tr		
Total Clay Cements	tr	5.50	8.00	5.50	0.50	5.00
Illite	tr	5.00	8.00	5.50	0.50	5.00
Kaolinite		0.50		tr		
Chlorite						
Total Porosity	4.50	9.00	16.00	12.50	2.00	6.00
Primary	1.50	7.00	10.50	11.00	1.50	3.50
Secondary	3.00	2.00	5.50	1.50	0.50	2.50
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00
% Total Quartz	72.22	78.06	73.38	72.73	81.82	76.71
% Total Feldspar	12.5	13.55	12.95	13.99	6.49	6.85
% Total Lithics	15.28	8.39	13.67	13.28	11.69	16.44

Lithological qualifyers

Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers

Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

Well 110/2-6			
Sample	**1189.30**	**1192.95**	**1195.55**
Stratigraphy	CSM	CSM	CSM
Facies	HSB	HSB	HSB
Lithology	SLA	SLA	SLA
Detrital Mineralogy			
Total Quartz	56.00	60.00	60.00
Monocrystalline	30.50	44.50	38.50
Polycrystalline Equant	11.50	8.00	10.00
Polycrystalline Schistose	10.50	6.50	10.00
Chert	3.50	1.00	1.50
Total Feldspar	3.00	6.00	4.50
K-Feldspar	2.00	5.50	4.50
Plagioclase	1.00	0.50	tr
Total Mica	0.50		tr
Muscovite	tr		tr
Biotite	0.50		
Chlorite			
Total Rock Fragments	13.00	12.50	10.50
Granitic	4.00	4.00	2.50
Volcanic	1.00		0.50
Metamorphic	8.00	8.50	7.50
Sedimentary			
Caliche			
Detrital Opaques			tr
Heavy Minerals	tr		tr
Organics			
Non-Resolvable Clays	tr	0.50	tr
Authigenic Mineralogy			
Total Blocky Cements	16.50	12.50	10.50
Non-Ferroan Calcite			
Ferroan Calcite			
Non-Ferroan Dolomite	8.50	2.00	1.50
Ferroan Dolomite	0.50	tr	0.50
Gypsum/Anhydrite			
Quartz	7.50	9.50	8.50
K-feldspar	tr		
Plagioclase			
Pyrite		tr	
Haematite	tr	1.00	tr
Anatase	tr	tr	
Total Clay Cements	3.00	3.00	4.00
Illite	2.50	3.00	3.00
Kaolinite	0.50		1.00
Chlorite			
Total Porosity	8.00	5.50	10.50
Primary	4.00	4.00	8.50
Secondary	4.00	1.50	2.00
TOTAL	100.00	100.00	100.00
% Total Quartz	77.24	76.43	80.00
% Total Feldspar	4.14	7.64	6.00
% Total Lithics	18.62	15.93	14.00

Lithological qualifyers	
Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW
Sub-qualifyers	
Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

Well 110/8a-5					
Sample	**1246.72**	**1258.85**	**1267.97**	**1277.22**	**1292.35**
Stratigraphy	OS2b	OS2b	OS2b	OS2a	OS2a
Facies	DES	AED	ASS	PAB	LSB
Lithology	aSFA	SFA	SFA	SFA	LA
Detrital Mineralogy					
Total Quartz	43.50	37.00	49.00	41.00	47.50
Monocrystalline	26.50	21.50	32.50	27.50	32.00
Polycrystalline Equant	13.50	11.50	12.00	10.50	7.50
Polycrystalline Schistose	3.00	2.00	3.00	0.50	5.00
Chert	0.50	2.00	1.50	2.50	3.00
Total Feldspar	15.00	17.00	17.00	15.00	5.50
K-Feldspar	12.50	13.50	14.00	12.50	5.00
Plagioclase	2.50	3.50	3.00	2.50	0.50
Total Mica	0.00	tr	tr	1.00	tr
Muscovite			tr	0.50	tr
Biotite				0.50	tr
Chlorite		tr			
Total Rock Fragments	10.50	13.50	10.00	14.00	18.00
Granitic	4.50	9.50	6.50	9.00	3.50
Volcanic		0.50			
Metamorphic	6.00	3.50	3.50	5.00	9.50
Sedimentary					
Caliche	tr		tr		5.00
Detrital Opaques		tr		tr	
Heavy Minerals		1.00	tr	tr	tr
Organics					
Non-Resolvable Clays	4.50	6.00	3.50	3.50	4.50
Authigenic Mineralogy					
Total Blocky Cements	26.50	8.00	9.50	7.50	15.00
Non-Ferroan Calcite					
Ferroan Calcite					
Non-Ferroan Dolomite	7.00	1.00	4.00	0.50	2.50
Ferroan Dolomite	0.50	1.50	3.00	0.50	1.00
Gypsum/Anhydrite	13.50	1.50			0.50
Quartz	5.50	3.50	2.50	4.50	8.50
K Feldspar		0.50		0.50	
Plagioclase				0.50	
Pyrite					
Haematite	tr	tr	tr	0.50	2.50
Anatase		tr		0.50	
Total Clay Cements	0.00	0.50	2.50	2.50	0.00
Illite		0.50	2.50	2.50	tr
Kaolinite					
Chlorite					
Total Porosity	0.00	17.00	8.50	15.50	9.50
Primary	tr	14.50	7.00	8.00	5.00
Secondary		2.50	1.50	7.50	4.50
TOTAL	100.00	100.00	100.00	100.00	100.00
% Total Quartz	63.04	54.01	64.47	58.57	66.90
% Total Feldspar	21.74	24.82	22.37	21.43	7.75
% Total Lithics	15.22	21.17	13.16	20.00	25.35

Lithological qualifyers	
Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers	
Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

Well 110/13-5						
Sample	**868.66**	**890.09**	**899.14**	**911.05**	**926.58**	**944.88**
Stratigraphy	OS2a	OS2a	OS2b	OS2b	OS2b	OS2b
Facies	AED	AED	LSB	ABT	PAB	IBC
Lithology	SFA	SFA	sSFA	LA	SLA	SLA
Detrital Mineralogy						
Total Quartz	43.50	46.50	41.50	39.00	58.50	56.00
Monocrystalline	28.00	25.50	29.50	25.50	31.50	32.00
Polycrystalline Equant	8.00	14.00	11.00	8.00	14.50	12.50
Polycrystalline Schistose	5.00	4.50	0.50	4.50	10.00	9.00
Chert	2.50	2.50	0.50	1.00	2.50	2.50
Total Feldspar	14.00	15.00	16.00	8.00	4.50	3.50
K-Feldspar	11.00	12.50	11.00	6.50	4.50	3.50
Plagioclase	3.00	2.50	5.00	1.50		
Total Mica	0.00	tr	tr	0.50	1.00	0.50
Muscovite		tr	tr	0.50	0.50	tr
Biotite		tr	tr	tr	0.50	0.50
Chlorite				tr		
Total Rock Fragments	12.50	14.00	15.00	23.00	12.00	12.50
Granitic	7.50	7.50	8.50	8.50	4.50	6.50
Volcanic	tr		0.50			
Metamorphic	5.00	6.50	6.00	14.50	7.50	6.00
Sedimentary						
Caliche		tr				
Detrital Opaques	tr		tr			
Heavy Minerals	tr	tr	tr	1.00	tr	tr
Organics						
Non-Resolvable Clays	tr	0.50	3.00	10.50	5.00	1.00
Authigenic Mineralogy						
Total Blocky Cements	15.00	6.50	12.50	5.00	11.50	11.00
Non-Ferroan Calcite				tr	tr	
Ferroan Calcite					tr	tr
Non-Ferroan Dolomite	6.00	1.50		0.50		
Ferroan Dolomite	2.50	2.00				
Gypsum/Anhydrite	tr	0.50	0.50	0.50		1.00
Quartz	6.00	2.00	10.50	2.50	8.50	9.50
K Feldspar	0.50	tr	1.00	0.50		0.50
Plagioclase			0.50			
Pyrite	tr	0.50			tr	
Haematite			tr	1.00	2.50	
Anatase		tr		tr	0.50	tr
Total Clay Cements	1.00	2.00	0.00	6.00	1.00	1.00
Illite	1.00	2.00	tr	6.00	1.00	1.00
Kaolinite		tr		tr	tr	
Chlorite						
Total Porosity	14.00	15.50	12.00	7.00	6.50	14.50
Primary	10.00	13.00	8.00	5.00	3.00	9.00
Secondary	4.00	2.50	4.00	2.00	3.50	5.50
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00
% Total Quartz	62.14	61.59	57.24	54.55	76.97	77.24
% Total Feldspar	20.00	19.87	22.07	11.19	5.92	4.83
% Total Lithics	17.86	18.54	20.69	34.26	17.11	17.93

Lithological qualifyers

Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers

Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

Well 110/14-3						
Sample	**1077.47**	**1082.05**	**1091.20**	**1100.00**	**1115.25**	**1127.40**
Stratigraphy	OS2b	OS2b	OS2b	OS2b	OS2b	OS2b
Facies	AED	DSF	AED	SFL	DSF	ASS
Lithology	SFA	SFA	SFA	SFA	dSFA	dSFA
Detrital Mineralogy						
Total Quartz	46.50	49.00	53.00	43.00	44.50	48.50
Monocrystalline	29.00	34.50	34.50	33.50	26.00	26.50
Polycrystalline Equant	11.00	12.00	13.50	6.50	13.00	13.50
Polycrystalline Schistose	2.50	1.50	3.50	3.00	4.00	6.00
Chert	4.00	1.00	1.50	tr	1.50	2.50
Total Feldspar	17.50	13.50	12.50	14.50	14.00	14.50
K-Feldspar	14.50	11.00	10.50	12.00	11.50	12.00
Plagioclase	3.00	2.50	2.00	2.50	2.50	2.50
Total Mica	0.50	tr		tr	tr	
Muscovite	0.50	tr		tr	tr	
Biotite						
Chlorite						
Total Rock Fragments	7.50	9.50	11.50	10.00	12.50	7.00
Granitic	4.50	7.00	4.50	6.50	7.00	4.00
Volcanic	0.50	tr	0.50		0.50	0.50
Metamorphic	1.50	2.50	6.50	3.50	4.50	2.50
Sedimentary					0.50	
Caliche	1.00	tr				
Detrital Opaques	tr	tr	tr	tr	0.50	
Heavy Minerals	tr	tr		0.50	tr	
Organics					tr	
Non-Resolvable Clays	4.50	3.50		8.00	1.00	0.50
Authigenic Mineralogy						
Total Blocky Cements	13.00	12.50	4.00	10.00	16.00	22.50
Non-Ferroan Calcite	0.50	2.50	1.00	0.50		
Non-Ferroan Dolomite	9.00			1.50	1.50	1.00
Ferroan Dolomite			tr	4.00	10.50	19.50
Gypsum/Anhydrite	0.5					
Quartz	3.50	8.50	2.50	3.00	3.00	2.00
K Feldspar	tr	0.50	tr		0.50	tr
Plagioclase						
Pyrite	tr	1.00	0.50	0.50	0.50	tr
Haematite				0.50		
Anatase					tr	tr
Total Clay Cements	6.50	3.00	1.50	6.00	1.50	0.00
Illite	6.00	3.00	1.50	5.50	1.50	tr
Kaolinite	0.50			0.50		
Chlorite						
Total Porosity	3.50	9.00	17.50	8.00	10.00	7.00
Primary	3.00	5.00	13.50	6.00	8.00	6.00
Secondary	0.50	4.00	4.00	2.00	2.00	1.00
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00
% Total Quartz	64.58	68.06	68.83	63.24	62.68	69.29
% Total Feldspar	24.31	18.75	16.23	21.32	19.72	20.71
% Total Lithics	11.11	13.19	14.94	15.44	17.60	10.00

Lithological descriptors

Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Qualifyers

Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

Well 110/14-3					
Sample	**1136.90**	**1154.58**	**1164.34**	**1173.48**	**1194.82**
Stratigraphy	OS2b	OS2a	OS2a	OS2a	OS2a
Facies					
Lithology	LA	QA	QA	dQA	QA
Detrital Mineralogy					
Total Quartz	39.00	58.50	56.00	59.50	59.00
Monocrystalline	25.50	31.50	32.00	31.00	35.50
Polycrystalline Equant	8.00	14.50	12.50	21.00	18.50
Polycrystalline Schistose	4.50	10.00	9.00	6.50	3.00
Chert	1.00	2.50	2.50	1.00	2.00
Total Feldspar	8.00	4.50	4.00	2.50	1.00
K-Feldspar	6.50	4.50	3.50	1.50	1.00
Plagioclase	1.50		0.50	1.00	
Total Mica	0.50	1.00	0.50	tr	tr
Muscovite	0.50	0.50	tr	tr	tr
Biotite	tr	0.50	0.50		
Chlorite	tr				
Total Rock Fragments	21.00	5.50	4.50	4.00	3.50
Granitic	8.50	5.50	7.50	3.00	2.50
Volcanic					
Metamorphic	12.50	8.50	5.00	2.00	1.50
Sedimentary					
Caliche					
Detrital Opaques					
Heavy Minerals	1.00	tr	tr	tr	tr
Organics					
Non-Resolvable Clays	10.50	5.00	1.00	0.50	9.00
Authigenic Mineralogy					
Total Blocky Cements	7.00	9.50	10.50	27.00	5.50
Non-Ferroan Calcite	tr	tr			
Non-Ferroan Dolomite	1.50			20.00	2.50
Ferroan Dolomite				1.00	tr
Gypsum/Anhydrite	0.50		1.00	0.50	tr
Quartz	3.50	6.50	9.00	5.50	3.00
K Feldspar	0.50		0.50		
Plagioclase					
Pyrite		tr			
Haematite	1.00	2.50			
Anatase	tr	0.50	tr	tr	tr
Total Clay Cements	6.00	1.00	1.00	3.00	10.00
Illite	6.00	1.00	1.00	1.50	6.50
Kaolinite	tr	tr		1.50	3.50
Chlorite					
Total Porosity	7.00	6.50	14.50	2.50	11.50
Primary	5.00	3.00	9.00	2.00	9.50
Secondary	2.00	3.50	5.50	0.50	2.00
TOTAL	100.00	100.00	100.00	100.00	100.00
% Total Quartz	56.12	84.17	86.15	90.15	92.91
% Total Feldspar	11.51	6.48	6.16	3.79	1.58
% Total Lithics	32.37	9.35	7.69	6.06	5.51

Lithological descriptors

Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Qualifyers

Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

Lancashire	Greetly
Sample	GR1
Stratigraphy	OSF
Facies	HSB
Lithology	sSLA
Detrital Mineralogy	
Total Quartz	55.00
Monocrystalline	35.00
Polycrystalline Equant	14.00
Polycrystalline Schistose	3.00
Chert	3.00
Total Feldspar	3.00
K-Feldspar	2.00
Plagioclase	1.00
Total Mica	tr
Muscovite	tr
Biotite	tr
Chlorite	
Total Rock Fragments	7.00
Granitic	3.00
Volcanic	
Metamorphic	4.00
Sedimentary	
Caliche	
Detrital Opaques	
Heavy Minerals	tr
Organics	
Non-Resolvable Clays	4.50
Authigenic Mineralogy	
Total Blocky Cements	13.50
Non-Ferroan Calcite	
Non-Ferroan Dolomite	
Ferroan Dolomite	
Gypsum/Anhydrite	
Quartz	13.50
K Feldspar	tr
Plagioclase	
Pyrite	
Haematite	tr
Anatase	
Total Clay Cements	0.50
Illite	0.50
Kaolinite	tr
Chlorite	
Total Porosity	16.50
Primary	14.50
Secondary	2.00
TOTAL	100.00
% Total Quartz	84.62
% Total Feldspar	4.61
% Total Lithics	10.77

Lithological qualifyers	
Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers	
Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

North Cheshire	Beeston Hill		Bickerton		Carden Park	
Sample	**BH1**	**BH2**	**BK1**	**BK2**	**CP1**	**CP2**
Stratigraphy	HSF	WSF	HSF	WSF	HSF	HSF
Facies	CPB	DRS	HSB	AED	HSB	HSB
Lithology	sSLA	SFA	sSLA	cSFA	SLA	cSLA
Detrital Mineralogy						
Total Quartz	47.50	46.50	47.50	52.50	42.00	48.50
Monocrystalline	30.50	37.00	26.50	35.00	24.50	28.50
Polycrystalline Equant	11.00	6.50	14.00	8.50	12.50	13.50
Polycrystalline Schistose	3.50	1.50	3.00	8.00	4.00	4.00
Chert	2.50	1.50	4.00	1.00	1.00	2.50
Total Feldspar	13.00	12.00	6.00	10.00	13.00	1.50
K-Feldspar	10.50	9.00	6.00	6.50	12.50	1.50
Plagioclase	2.50	3.00	tr	3.50	0.50	
Total Mica	tr	0.50	tr	1.00	1.50	0.50
Muscovite	tr	0.50	tr	0.50	1.00	
Biotite	tr	tr	tr	0.50	0.50	0.50
Chlorite						
Total Rock Fragments	19.00	9.00	14.00	5.50	12.00	11.50
Granitic	6.50	4.00	5.50	2.50	3.50	2.50
Volcanic		tr	0.50			
Metamorphic	10.50	5.00	7.00	2.00	8.00	8.50
Sedimentary	2.00		tr	0.50		
Caliche			1.00			
Detrital Opaques		tr		0.50		
Heavy Minerals	tr	tr		tr	tr	
Organics	tr				0.50	0.50
Non-Resolvable Clays	1.00	12.50	2.00	4.50	6.50	5.50
Authigenic Mineralogy						
Total Blocky Cements	12.50	8.50	22.00	18.50	12.50	28.00
Non-Ferroan Calcite			9.00	16.00		27.50
Non-Ferroan Dolomite			tr	tr		
Ferroan Dolomite						
Gypsum/Anhydrite			1.50	0.50		
Quartz	12.00	8.50	11.00	1.50	9.00	0.50
K Feldspar					1.00	
Plagioclase						
Pyrite	0.50					
Haematite		tr	0.50	0.50	2.50	tr
Anatase						
Total Clay Cements	0.00	1.00	1.00	1.50	0.00	0.00
Illite		0.50	1.00	1.50		
Kaolinite		0.50				
Chlorite						
Total Porosity	7.00	10.00	7.50	6.50	12.50	4.50
Primary	5.50	6.00	6.00	5.50	8.50	3.50
Secondary	1.50	4.00	1.50	1.00	4.00	1.00
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00
% Total Quartz	59.75	68.89	70.37	76.09	61.31	78.23
% Total Feldspar	16.35	17.78	8.89	14.49	18.98	2.42
% Total Lithics	23.90	13.33	20.74	9.42	19.71	19.35

Lithological qualifyers

Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers

Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

North Cheshire	Carden	Helsby Hill				
Sample	**CP3**	**HH1**	**HH2**	**HH3**	**HH4**	**HH5**
Stratigraphy	WSF	HSF	HSF	HSF	WSF	WSF
Facies	AED	HSB	LSB	HSB	AED	ASS
Lithology	SFSLA	SLA	sSLA	sSLA	SLA	SFA
Detrital Mineralogy						
Total Quartz	54.50	44.00	44.50	46.00	59.00	50.50
Monocrystalline	34.50	26.00	26.50	23.50	34.00	27.50
Polycrystalline Equant	13.00	14.00	13.50	15.50	16.50	18.50
Polycrystalline Schistose	3.50	3.00	2.00	3.50	5.00	3.00
Chert	3.50	1.00	2.50	3.50	3.50	1.50
Total Feldspar	8.00	11.00	11.00	9.00	7.00	11.00
K-Feldspar	7.50	10.50	11.00	9.00	6.50	10.50
Plagioclase	0.50	0.50	t	tr	0.50	0.50
Total Mica	0.00	1.50	tr	tr	tr	0.00
Muscovite		1.00	tr	tr	tr	
Biotite		0.50		tr		
Chlorite			tr			
Total Rock Fragments	8.00	14.00	13.00	15.50	11.50	6.50
Granitic	3.00	5.50	6.00	9.00	4.00	3.50
Volcanic		0.50			0.50	
Metamorphic	5.00	7.50	6.50	5.00	6.00	3.00
Sedimentary		0.50	0.50	1.00	0.50	
Caliche					0.50	
Detrital Opaques	tr	tr	tr	tr	tr	
Heavy Minerals		tr	tr	tr	tr	tr
Organics				0.50		
Non-Resolvable Clays	5.00	3.00	0.50	5.00	4.00	8.00
Authigenic Mineralogy						
Total Blocky Cements	1.50	8.50	17.00	11.00	1.00	1.00
Non-Ferroan Calcite						
Non-Ferroan Dolomite						
Ferroan Dolomite						
Gypsum/Anhydrite		1.00	2.50			0.50
Quartz	1.00	6.00	10.50	10.50	1.00	0.50
K Feldspar		0.50	1.50	tr		
Plagioclase						
Pyrite						
Haematite	0.50	1.00	2.50	tr	tr	tr
Anatase				0.50		
Total Clay Cements	1.00	1.50	2.00	0.50	5.00	3.00
Illite	1.00	1.00	2.00	0.50	5.00	3.00
Kaolinite		0.50				
Chlorite						
Total Porosity	22.00	16.50	12.00	13.00	12.50	20.00
Primary	18.50	11.00	11.00	9.00	11.00	16.50
Secondary	3.50	5.50	1.00	4.00	1.50	3.50
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00
% Total Quartz	77.30	62.41	64.96	64.79	76.13	74.26
% Total Feldspar	11.35	15.60	16.06	12.68	9.03	16.18
% Total Lithics	11.35	21.99	18.98	22.53	14.84	9.56

Lithological qualifyers

Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers

Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

North Cheshire	Moss Fm	Raw Head		
Sample	**MF1**	**RH1**	**RH2**	**RH3**
Stratigraphy	WSF	HSF	WSF	WSF
Facies	HSB	HSB	LSB	AED
Lithology	SLFA	cLA	SLA	sLA
Detrital Mineralogy				
Total Quartz	44.50	23.50	49.00	45.00
Monocrystalline	29.00	7.00	27.50	28.50
Polycrystalline Equant	9.50	10.00	12.00	10.00
Polycrystalline Schistose	4.00	3.50	6.50	4.50
Chert	2.00	3.00	3.00	2.00
Total Feldspar	14.00	8.50	7.00	5.50
K-Feldspar	11.50	8.50	7.00	5.50
Plagioclase	2.50		tr	
Total Mica	tr	tr	tr	0.50
Muscovite	tr	tr	tr	
Biotite			tr	0.50
Chlorite				
Total Rock Fragments	14.00	28.00	16.50	17.50
Granitic	9.00	6.50	7.00	6.00
Volcanic				0.50
Metamorphic	4.50	2.50	9.50	11.00
Sedimentary		3.50		
Caliche		15.50		
Detrital Opaques	tr		tr	
Heavy Minerals	0.50		tr	tr
Organics	tr			
Non-Resolvable Clays	1.50	1.00	1.50	3.00
Authigenic Mineralogy				
Total Blocky Cements	5.50	33.00	9.00	11.50
Non-Ferroan Calcite		29.00		
Non-Ferroan Dolomite				
Ferroan Dolomite				
Gypsum/Anhydrite				
Quartz	5.00	2.50	8.00	11.00
K Feldspar	tr	0.50	1.00	tr
Plagioclase				
Pyrite				
Haematite		1.00	tr	0.50
Anatase	0.50			
Total Clay Cements	tr	tr	1.00	2.00
Illite	tr		1.00	tr
Kaolinite		tr	tr	2.00
Chlorite				
Total Porosity	20.50	6.00	16.00	15.00
Primary	17.00	3.50	13.50	11.50
Secondary	3.50	2.50	2.50	3.50
TOTAL	100.00	100.00	100.00	100.00
% Total Quartz	61.38	39.17	67.59	65.69
% Total Feldspar	19.31	14.17	9.65	8.03
% Total Lithics	19.31	46.66	22.76	26.28

Lithological qualifyers

Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers

Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

North Wirral	Hilbre Point				New Brighton	
Sample	**HP1**	**HP2**	**HP3**	**HP4**	**NB1**	**NB2**
Stratigraphy	OSF	OSF	OSF	OSF	OSF	OSF
Facies	HSB	LSB	HSB	HSB	AED	HSB
Lithology	SLA	SLA	SLA	SLA	SLA	SLA
Detrital Mineralogy						
Total Quartz	47.00	53.50	49.00	51.50	53.00	49.50
Monocrystalline	27.00	31.00	29.00	32.50	28.00	26.50
Polycrystalline Equant	12.00	13.50	11.50	13.50	15.50	16.00
Polycrystalline Schistose	4.00	4.00	5.00	4.00	6.50	4.50
Chert	4.00	5.00	3.50	1.50	3.00	2.50
Total Feldspar	7.00	6.50	6.50	4.50	8.00	5.50
K-Feldspar	6.00	6.50	6.50	4.50	7.50	5.00
Plagioclase	1.00	tr			0.50	0.50
Total Mica	tr	tr		tr	tr	
Muscovite				tr	tr	
Biotite	tr	tr		tr		
Chlorite						
Total Rock Fragments	15.00	14.50	12.50	15.00	9.50	13.00
Granitic	6.00	5.00	3.50	7.00	4.00	6.50
Volcanic		0.50	0.50	0.50	0.50	
Metamorphic	8.00	8.00	7.50	7.00	3.50	5.50
Sedimentary	1.00	1.00	1.00			
Caliche	tr			0.50	0.50	
Detrital Opaques					0.50	
Heavy Minerals		tr			0.50	tr
Organics						1.00
Non-Resolvable Clays	4.00	2.50	12.00	3.50	6.00	0.50
Authigenic Mineralogy						
Total Blocky Cements	7.50	9.50	5.00	7.00	3.50	7.50
Non-Ferroan Calcite						
Non-Ferroan Dolomite						
Ferroan Dolomite					2.00	
Gypsum/Anhydrite						
Quartz	7.00	8.50	4.50	6.00	1.00	7.50
K Feldpspar	0.50	0.50	tr	0.50	0.50	tr
Plagioclase						
Pyrite						
Haematite		0.50	0.50	0.50	tr	
Anatase						
Total Clay Cements	1.50	1.50	1.50	1.00	3.00	2.50
Illite	1.50	1.50	1.50	1.00	3.00	2.50
Kaolinite						
Chlorite						
Total Porosity	18.00	12.00	13.50	17.50	17.00	21.50
Primary	14.00	10.50	9.50	12.00	8.50	17.00
Secondary	4.00	1.50	4.00	5.50	8.50	4.50
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00
% Total Quartz	68.12	71.81	72.06	72.54	75.18	72.79
% Total Feldspar	10.14	8.73	9.56	6.34	11.35	8.09
% Total Lithics	21.74	19.46	18.38	21.12	13.47	19.12

Lithological qualifyers

Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers

Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

North Wirral	N Brighton	Thurstaston Rd Ctg	
Sample	**NB3**	**TRC1**	**TRC2**
Stratigraphy	OSF	StBSF	StBSF
Facies	SFL	HSB	AED
Lithology	SLA	sSLA	SLA
Detrital Mineralogy			
Total Quartz	47.50	46.50	59.50
Monocrystalline	37.50	33.00	34.50
Polycrystalline Equant	6.50	11.50	15.00
Polycrystalline Schistose	1.50	0.50	4.50
Chert	2.00	1.50	5.50
Total Feldspar	9.50	10.50	2.50
K-Feldspar	9.00	9.00	2.50
Plagioclase	0.50	1.50	
Total Mica	0.50	tr	tr
Muscovite	0.50	tr	tr
Biotite	tr	tr	tr
Chlorite			
Total Rock Fragments	11.00	11.00	11.00
Granitic	8.00	4.00	4.50
Volcanic			
Metamorphic	3.00	6.00	6.50
Sedimentary			
Caliche		0.50	
Detrital Opaques	tr	0.50	tr
Heavy Minerals	tr	tr	tr
Organics			tr
Non-Resolvable Clays	6.00	4.50	7.50
Authigenic Mineralogy			
Total Blocky Cements	4.00	13.50	3.50
Non-Ferroan Calcite			
Non-Ferroan Dolomite			
Ferroan Dolomite			
Gypsum/Anhydrite			
Quartz	3.00	11.00	0.50
K Feldpspar	0.50	tr	
Plagioclase			
Pyrite			
Haematite	0.50	2.50	3.00
Anatase	tr		
Total Clay Cements	6.50	0.00	1.00
Illite	6.00		0.50
Kaolinite	0.50		0.50
Chlorite			
Total Porosity	15.00	14.00	15.00
Primary	10.00	9.00	13.50
Secondary	5.00	5.00	1.50
TOTAL	100.00	100.00	100.00
% Total Quartz	69.34	67.88	81.51
% Total Feldspar	13.87	15.33	3.42
% Total Lithics	16.79	16.79	15.07

Lithological qualifyers	
Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers	
Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

South Cheshire	Alberbury	Nesscliffe	P' Brock'	Red Hills		
Sample	**AB1**	**NC1**	**PB1**	**RD1**	**RD2**	**RD3**
Stratigraphy						
Facies	ALF	ASS	ASS	HSB	SFL	DSF
Lithology	dSLA	SLA	SLA	LA	SLW	LA
Detrital Mineralogy						
Total Quartz	18.50	45.50	53.00	38.50	42.50	40.00
Monocrystalline	16.50	32.50	28.50	22.50	28.50	27.00
Polycrystalline Equant	1.50	7.00	14.00	10.00	11.00	7.00
Polycrystalline Schistose	0.50	1.50	3.00	5.00		1.50
Chert	tr	4.50	7.50	1.00	3.00	4.50
Total Feldspar	0.50	9.50	7.50	10.00	9.50	10.50
K-Feldspar	0.50	9.50	7.00	10.00	7.50	9.50
Plagioclase			0.50	tr	2.00	1.00
Total Mica		tr	tr	0.50	3.50	2.50
Muscovite		tr	tr	0.50	2.00	1.50
Biotite					1.50	1.00
Chlorite						
Total Rock Fragments	2.50	10.00	13.50	20.00	7.00	15.50
Granitic		2.50	4.00	7.00	3.50	5.00
Volcanic		0.50	0.50	1.00		0.50
Metamorphic	2.00	6.00	9.00	12.00	3.00	8.50
Sedimentary						
Caliche	tr					
Detrital Opaques		1.00		tr	0.50	1.00
Heavy Minerals	0.50	tr	tr	tr	tr	0.50
Organics			tr			
Non-Resolvable Clays	5.00	7.50	0.50	6.00	25.50	12.50
Authigenic Mineralogy						
Total Blocky Cements	71.50	1.00	3.00	10.00	4.50	4.00
Non-Ferroan Calcite	0.50					
Non-Ferroan Dolomite	70.50					
Ferroan Dolomite						
Gypsum/Anhydrite						
Quartz		0.50	3.00	4.00	1.50	2.50
K Feldspar				1.00		
Plagioclase						
Pyrite						
Haematite	0.50	0.50	tr	5.00	3.00	1.50
Anatase		tr				
Total Clay Cements	0.00	3.00	4.50	0.50	3.50	5.00
Illite		2.50	4.50	0.50	2.50	3.00
Kaolinite		0.50		tr	1.00	2.00
Chlorite	tr					
Total Porosity	2.00	23.50	18.00	14.50	4.00	10.00
Primary	1.00	20.50	15.50	9.50	tr	3.00
Secondary	1.00	3.00	2.50	5.00	4.00	7.00
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00
% Total Quartz	86.05	70.00	71.62	55.80	67.46	57.14
% Total Feldspar	2.32	14.62	10.14	14.49	15.08	15.00
% Total Lithics	11.63	15.38	18.24	29.71	17.46	27.86

Lithological qualifyers

Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers

Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

South Cheshire	The Cliffe
Sample	**TC1**
Stratigraphy	
Facies	AED
Lithology	SFA
Detrital Mineralogy	
Total Quartz	48.00
Monocrystalline	31.50
Polycrystalline Equant	12.00
Polycrystalline Schistose	1.50
Chert	3.00
Total Feldspar	13.00
K-Feldspar	12.00
Plagioclase	1.00
Total Mica	tr
Muscovite	tr
Biotite	tr
Chlorite	
Total Rock Fragments	8.50
Granitic	2.00
Volcanic	tr
Metamorphic	6.50
Sedimentary	
Caliche	
Detrital Opaques	tr
Heavy Minerals	
Organics	tr
Non-Resolvable Clays	6.00
Authigenic Mineralogy	
Total Blocky Cements	1.50
Non-Ferroan Calcite	
Non-Ferroan Dolomite	
Ferroan Dolomite	
Gypsum/Anhydrite	
Quartz	1.00
K Feldspar	tr
Plagioclase	
Pyrite	tr
Haematite	0.50
Anatase	
Total Clay Cements	5.00
Illite	5.00
Kaolinite	
Chlorite	
Total Porosity	18.00
Primary	14.00
Secondary	4.00
TOTAL	100.00
% Total Quartz	69.06
% Total Feldspar	18.71
% Total Lithics	12.23

Lithological qualifyers

Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers

Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

South Wirral	Bromborough		Burton Point		
Sample	**BB1**	**BB2**	**BP1**	**BP2**	**BP3**
Stratigraphy	CPBF	CPBF	CPBF	CPBF	KSF
Facies	HSB	HSB	HSB	HSB	AED
Lithology	LA	SLA	SLA	SLA	SFA
Detrital Mineralogy					
Total Quartz	40.50	38.50	50.50	52.50	54.00
Monocrystalline	20.50	23.50	32.50	28.00	37.50
Polycrystalline Equant	11.50	8.50	10.00	15.50	10.50
Polycrystalline Schistose	6.50	4.00	4.50	4.50	3.00
Chert	2.00	2.50	3.50	4.50	3.00
Total Feldspar	9.00	12.00	11.00	9.00	11.00
K-Feldspar	8.50	12.00	10.50	9.00	10.00
Plagioclase	0.50	tr	0.50	tr	1.00
Total Mica	0.50	tr	tr	1.50	tr
Muscovite	tr	tr	tr	1.00	tr
Biotite	0.50	tr	tr	0.50	tr
Chlorite					
Total Rock Fragments	16.00	15.50	11.50	12.50	10.00
Granitic	3.50	3.50	2.50	2.50	1.50
Volcanic	0.50	1.00	1.00	2.50	1.00
Metamorphic	10.00	10.50	7.50	6.50	7.50
Sedimentary	2.00	0.50		1.00	
Caliche	tr				
Detrital Opaques			0.50		tr
Heavy Minerals	tr		tr		
Organics					
Non-Resolvable Clays	4.50	7.00	5.00	3.00	8.50
Authigenic Mineralogy					
Total Blocky Cements	12.00	12.00	6.50	3.00	2.00
Non-ferroan Calcite					
Non-Ferroan Dolomite					
Ferroan Dolomite	2.00				
Gypsum/Anhydrite					
Quartz	5.50	6.00	3.50	1.00	1.00
K Feldspar	0.50	0.50	0.50		
Plagioclase					
Pyrite					
Haematite	4.00	5.50	2.50	1.50	1.00
Anatase				0.50	
Total Clay Cements	1.00	2.00	1.50	4.00	0.50
Illite	1.00	2.00	1.50	4.00	0.50
Kaolinite				tr	
Chlorite					
Total Porosity	16.50	13.00	14.00	14.50	14.00
Primary	11.00	8.50	9.00	11.50	11.50
Secondary	5.50	4.50	5.00	3.00	2.50
TOTAL	100.00	100.00	100.00	100.00	100.00
% Total Quartz	61.36	58.33	69.18	69.54	72.00
% Total Feldspar	13.64	18.18	15.07	11.92	14.67
% Total Lithics	25.00	23.49	15.75	18.54	13.33

Lithological qualifyers

Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers

Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

West Cumbria	St Bees S	Fleswick Bay				Saltom Bay
Sample	**SB1**	**FC1**	**FC2**	**FC3**	**FC4**	**ST1**
Stratigraphy	StBSF	StBSF	StBSF	StBSF	StBSF	StBSF
Facies	HSB	HSB	LSB	LSB	LSB	HSB
Lithology	FA	LA	FA	FA	dFA	SFA
Detrital Mineralogy						
Total Quartz	38.00	34.50	38.50	29.00	34.50	36.00
Monocrystalline	27.50	22.50	29.00	20.00	23.50	29.50
Polycrystalline Equant	7.00	7.00	7.00	8.50	8.00	5.00
Polycrystalline Schistose	1.00	3.00	tr	0.50	1.50	1.50
Chert	2.50	2.00	2.50	tr	1.50	tr
Total Feldspar	15.00	14.00	15.50	23.00	14.00	15.00
K-Feldspar	12.50	12.00	11.50	16.50	11.50	11.50
Plagioclase	2.50	2.00	4.00	6.50	2.50	3.50
Total Mica	tr	tr	0.50	4.00	1.00	1.00
Muscovite	tr	tr	0.50	3.00	0.50	0.50
Biotite	tr		tr	1.00	0.50	0.50
Chlorite				tr		
Total Rock Fragments	6.00	17.50	6.50	6.50	5.00	9.50
Granitic	4.00	7.00	5.50	3.50	1.50	3.50
Volcanic	0.50	0.50		0.50	0.50	
Metamorphic	1.50	9.50	1.00	0.50	3.00	5.00
Sedimentary		0.50		1.00		0.50
Caliche	tr			1.00		0.50
Detrital Opaques	0.50	tr	tr	1.00		tr
Heavy Minerals	tr		tr	0.50	1.00	tr
Organics		1.00				
Non-Resolvable Clays	8.50	4.00	9.00	5.00	10.00	8.50
Authigenic Mineralogy						
Total Blocky Cements	15.50	10.00	15.00	11.50	22.50	18.00
Non-Ferroan Calcite	0.50				1.00	tr
Non-Ferroan Dolomite	5.00			2.50	10.50	7.00
Ferroan Dolomite						tr
Gypsum/Anhydrite						
Quartz	3.50	9.00	9.50	5.50	5.50	5.50
K-feldspar	tr	tr	1.50	1.00	0.50	
Plagioclase						
Pyrite						
Haematite	7.00	1.00	4.00	2.50	5.00	5.50
Anatase			tr			
Total Clay Cements	0.00	0.50	1.00	8.00	1.00	0.00
Illite		0.50	1.00	8.00	1.00	
Kaolinite		tr				
Chlorite						
Total Porosity	16.00	18.50	14.00	11.50	11.00	12.00
Primary	10.00	14.00	9.50	5.00	7.00	6.50
Secondary	6.00	4.50	4.50	6.50	4.00	5.50
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00
% Total Quartz	63.87	51.49	63.11	45.31	62.16	58.54
% Total Feldspar	25.21	20.90	25.41	35.94	25.23	24.39
% Total Lithics	10.92	27.61	11.48	12.50	12.61	17.07

Lithological qualifyers

Quartz arenite	QA
Sub-feldspathic arenite	SFA
Sub-lithic arenite	SLA
Feldspathic arenite	FA
Lithic arenite	LA
Quartz wacke	QW

Sub-qualifyers

Dolomitic	d
Illitic	I
Siliceous	s
Anhydritic	a

APPENDIX IV

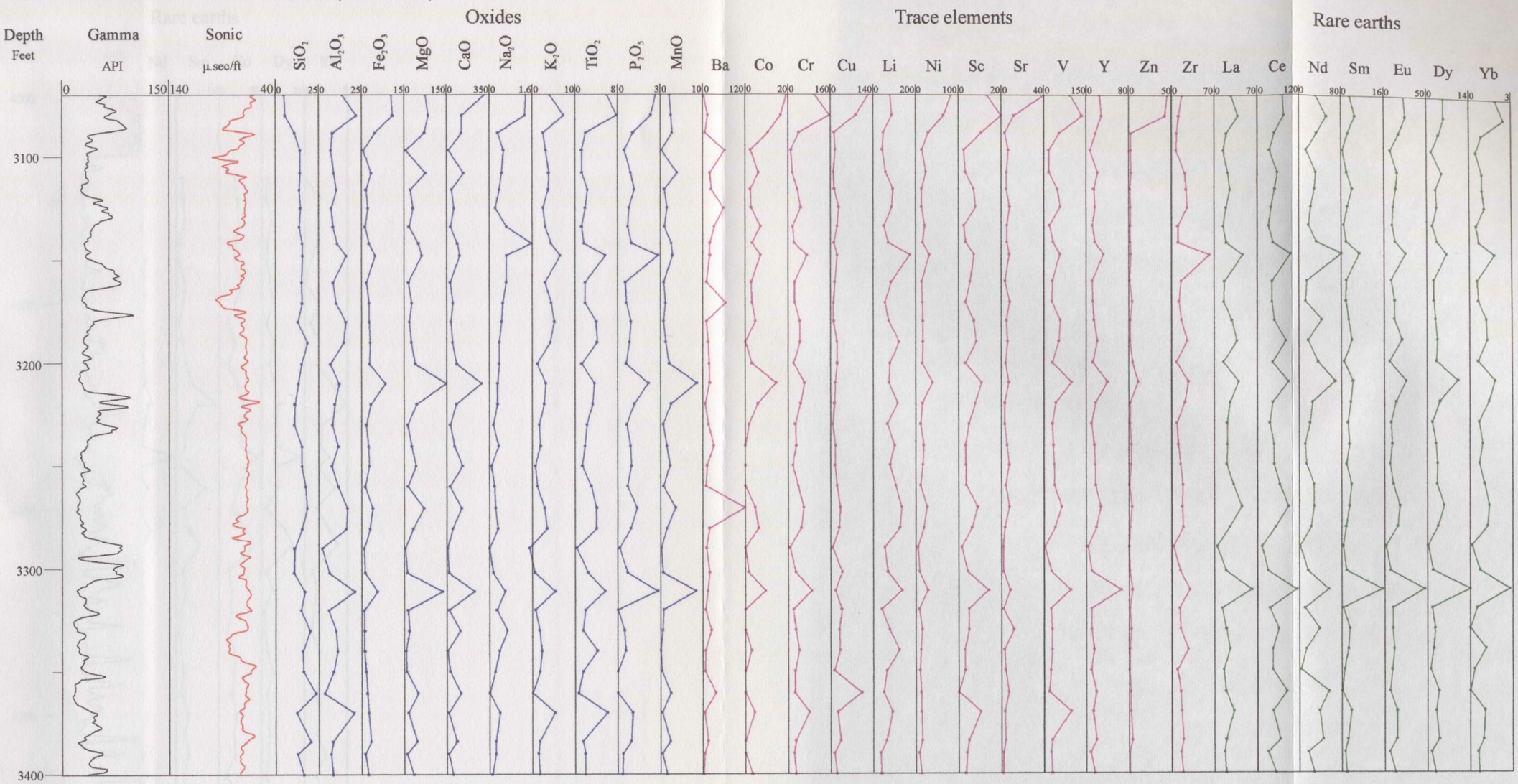
ICP-AES and ICP-MS Geochemical Data

Raw data (tabulated and normalised data (plotted)

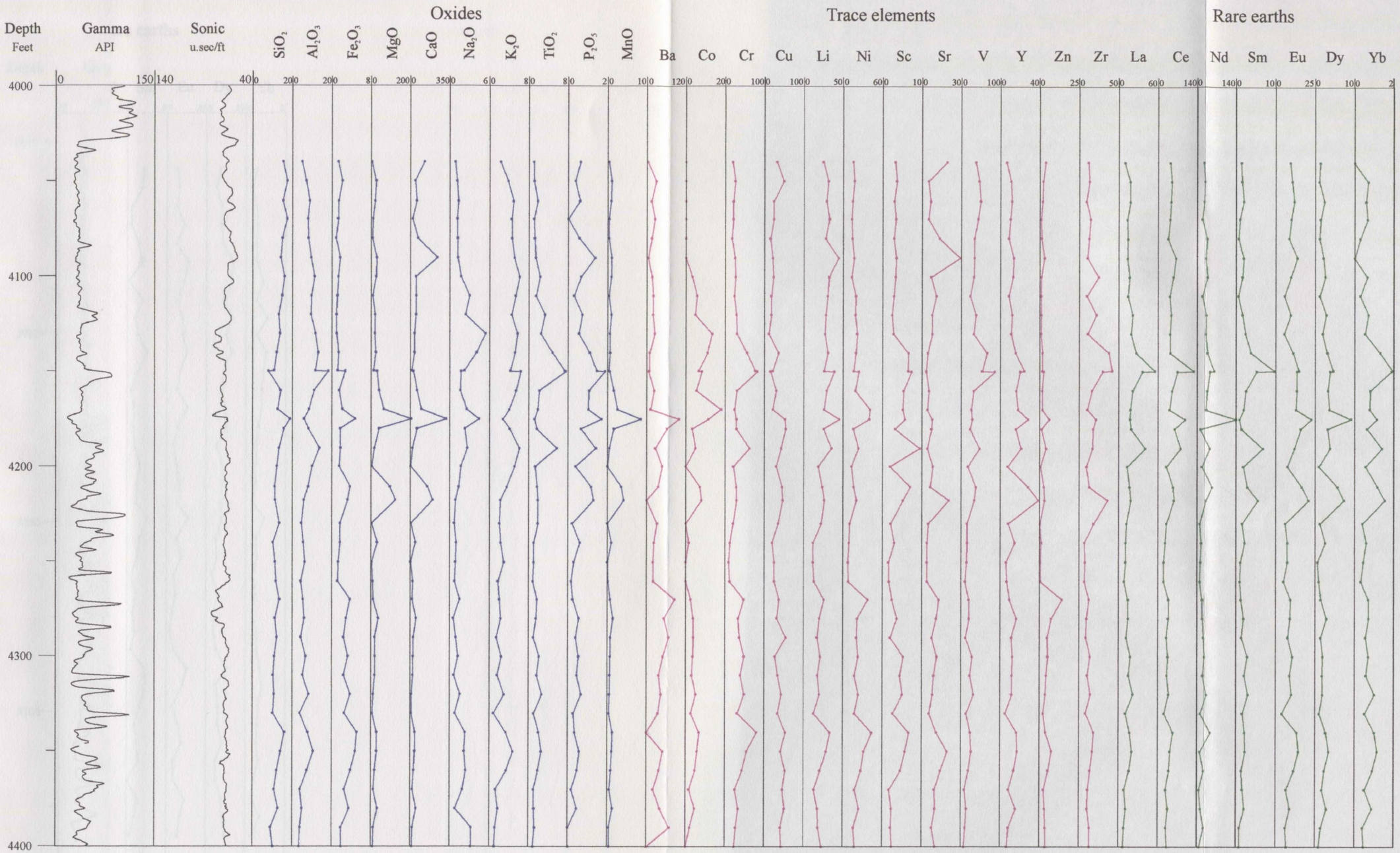
Well	Depth (ft)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Ba	Co	Cr	Cu	Li	Ni	Sc	Sr	V	Y	Zn	Zr	La	Ce	Nd	Sm	Eu	Dy	Yb
110/2-6	**3070.00**	34.44	7.20	5.50	3.84	16.39	0.72	2.40	0.31	0.14	0.11	47	10	52	65	41	43	7	632	49	13	236	125	14	38	17	1.8	1.2	2.9	1
	3080.00	41.81	13.24	6.58	5.07	7.40	0.80	4.56	0.47	0.14	0.15	822	10	94	50	52	39	12	211	81	17	255	96	23	46	32	3.1	1.5	3.4	1.5
	3088.50	73.89	3.80	2.13	3.30	5.66	0.14	1.53	0.09	0.05	0.13	276	5	19	5	22	14	5	44	26	8	10	56	9	23	16	1.2	0.8	1.8	0.4
	3097.00	93.10	3.13	0.26	0.27	0.52	0.22	1.64	0.05	0.02	0.01	2624	1	4	6	18	6	1	84	7	3	9	45	6	15	6	0.2	0.3	0.6	0.2
	3108.20	81.17	2.92	1.10	2.47	4.56	0.15	1.47	0.04	0.03	0.13	626	2	5	3	19	8	1	48	6	7	9	102	7	19	11	0.7	0.5	1.6	0.3
	3116.00	89.46	4.54	0.65	0.92	1.69	0.16	1.89	0.10	0.05	0.04	998	1	15	5	40	6	3	57	21	6	5	145	11	22	13	1.8	0.6	1.2	0.4
	3125.00	88.13	2.81	0.82	1.16	2.25	0.08	1.23	0.07	0.03	0.06	2188	1	18	10	33	5	3	86	22	6	7	137	7	15	8	0.9	0.4	1.2	0.4
	3134.00	89.37	3.63	0.49	0.74	1.29	0.27	1.61	0.05	0.03	0.04	1357	3	7	9	21	9	1	64	8	5	6	60	6	14	8	0.4	0.4	0.7	0.2
	3142.00	85.88	3.36	0.80	1.55	2.69	0.49	1.53	0.05	0.03	0.08	591	1	7	3	22	5	1	47	10	5	5	46	6	14	10	0.6	0.4	1	0.2
	3148.00	83.09	4.53	1.33	1.72	2.96	0.18	1.93	0.16	0.08	0.08	551	2	20	6	49	9	2	61	16	9	6	249	13	27	23	1.9	0.7	1.8	0.5
	3161.00	92.20	3.15	0.64	0.55	1.03	0.23	1.39	0.07	0.02	0.03	367	1	9	5	31	5	2	37	11	4	3	81	6	16	5	0.7	0.3	0.8	0.2
	3171.00	87.94	3.39	0.87	0.87	1.62	0.16	1.64	0.06	0.02	0.04	2099	1	8	3	18	5	1	75	9	4	13	55	5	14	4	0.5	0.4	0.7	0.2
	3180.00	83.30	6.83	1.12	0.76	1.44	0.19	2.42	0.17	0.04	0.03	420	2	19	4	31	7	3	59	25	6	7	95	12	21	18	1.2	0.5	1.1	0.5
	3190.00	91.27	3.61	0.74	0.61	1.18	0.09	1.17	0.10	0.02	0.03	339	0	11	5	30	4	2	42	13	5	3	89	9	20	4	1.0	0.5	0.8	0.3
	3200.50	87.75	2.34	0.92	1.32	2.72	0.12	0.69	0.04	0.02	0.07	590	1	7	7	26	5	1	38	10	4	15	37	5	15	12	0.3	0.2	1	0.2
	3210.00	68.52	3.36	2.34	4.16	7.99	0.08	1.06	0.10	0.06	0.24	516	4	17	4	20	11	3	57	27	11	30	108	11	25	19	1.2	0.7	2.8	0.5
	3220.00	78.48	4.84	1.69	2.27	4.04	0.15	1.80	0.17	0.06	0.13	306	3	24	6	59	8	4	46	22	9	8	157	13	23	13	1.8	0.7	2.1	0.7
	3230.00	85.04	5.24	1.04	0.75	1.73	0.09	1.60	0.14	0.04	0.04	1005	1	17	4	43	7	3	55	19	6	6	79	13	23	13	1.5	0.5	1	0.4
	3240.50	87.97	3.85	0.79	0.88	2.13	0.11	0.90	0.06	0.03	0.05	981	0	10	5	33	6	1	51	11	5	9	50	7	16	4	1.0	0.3	0.9	0.3
	3250.00	84.19	2.36	0.82	1.26	3.97	0.02	0.49	0.04	0.03	0.07	338	0	5	4	24	5	1	64	11	5	7	62	6	15	4	0.6	0.2	1	0.2
	3260.00	93.49	3.39	0.35	0.39	0.76	0.05	0.60	0.09	0.02	0.02	222	0	11	6	31	3	1	33	11	5	1	75	9	19	8	1.1	0.3	0.9	0.3
	3270.70	86.36	3.74	0.86	1.55	2.74	0.05	0.80	0.09	0.03	0.08	2670	1	13	7	30	6	2	50	14	6	8	53	10	20	6	0.6	0.4	1.2	0.3
	3280.60	87.56	5.28	0.94	1.01	1.57	0.10	1.34	0.13	0.03	0.05	581	2	16	9	41	6	2	29	13	6	4	86	8	17	7	0.5	0.5	1.1	0.4
	3290.00	97.22	1.46	0.67	0.24	0.42	0.00	0.26	0.02	0.01	0.01	753	0	4	4	44	3	1	32	2	2	0	33	3	11	1	0.4	0.1	0.1	0.1
	3302.00	89.65	4.62	0.88	0.77	1.21	0.09	1.10	0.18	0.05	0.04	1341	1	21	28	50	6	3	35	19	7	5	143	14	23	12	1.3	0.5	1.3	0.5
	3311.00	77.44	4.51	1.17	2.90	4.86	0.12	1.23	0.12	0.06	0.18	291	2	19	3	29	6	3	52	20	14	8	89	13	24	12	3.2	1	3	0.6
	3320.00	95.03	2.48	0.34	0.53	0.72	0.11	0.68	0.08	0.00	0.03	262	0	8	15	16	3	2	21	10	4	3	74	5	15	4	0.2	0.4	0.6	0.2
	3330.00	91.57	2.13	0.21	0.37	2.35	0.14	0.53	0.03	0.01	0.01	485	0	6	6	16	3	1	73	6	2	5	42	4	13	8	0.6	0.2	0.5	0
	3340.00	94.26	3.97	0.36	0.22	0.13	0.13	1.06	0.15	0.02	0.00	244	1	15	11	44	4	1	28	10	5	2	136	9	16	5	0.9	0.4	0.7	0.4
	3350.00	94.32	3.02	0.51	0.27	0.85	0.07	0.89	0.05	0.00	0.01	174	0	9	4	22	3	1	37	8	3	1	43	5	15	1	0.3	0.3	0.3	0.1
	3360.50	94.52	0.58	0.31	0.81	1.91	0.00	0.18	0.01	0.00	0.04	590	0	4	17	8	2	0	33	3	3	3	34	3	14	9	0.0	0.1	0.6	0
	3370.00	83.19	9.91	1.16	0.69	0.68	0.18	2.77	0.29	0.05	0.02	182	2	38	11	43	6	5	42	46	6	9	107	15	22	18	1.8	0.7	1.3	0.5
	3384.00	93.20	1.74	0.69	0.94	1.76	0.05	0.54	0.03	0.02	0.05	296	0	6	7	13	3	1	22	6	4	8	56	4	14	10	0.5	0.3	0.8	0.2
	3390.00	92.56	3.98	0.67	0.49	0.73	0.13	1.22	0.10	0.02	0.02	197	0	12	6	18	4	2	24	13	4	2	113	9	17	9	0.7	0.3	0.7	0.3
	3400.00	91.74	2.64	0.71	1.04	1.63	0.03	0.80	0.06	0.01	0.05	33	1	9	6	12	4	1	14	9	5	2	82	6	17	9	0.6	0.4	0.8	0.2

Well	Depth (ft)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Ba	Co	Cr	Cu	Li	Ni	Sc	Sr	V	Y	Zn	Zr	La	Ce	Nd	Sm	Eu	Dy	Yb
110/8a-5	**4000.00**	48.90	12.33	5.85	3.97	5.87	3.41	3.78	0.50	0.14	0.10	144	10	71	24	56	38	11	352	76	17	66	115	26	55	35	4.5	1.5	3.4	1.6
	4010.00	49.24	12.35	5.88	3.74	4.59	5.52	3.85	0.52	0.13	0.09	268	12	80	23	55	39	11	246	78	18	60	134	27	58	28	3.9	1.5	3.3	1.6
	4020.00	33.32	7.90	3.94	2.95	10.65	9.90	2.56	0.34	0.11	0.08	81	7	33	16	40	27	8	470	51	13	49	81	14	33	17	2.3	1.1	2.3	0.9
	4030.00	65.39	2.89	2.09	0.74	2.50	10.00	1.28	0.08	0.02	0.04	209	3	45	31	15	25	2	262	22	5	33	60	5	17	11	0.5	0.5	0.7	0.3
	4040.00	72.59	2.84	1.05	0.85	2.12	8.04	1.51	0.08	0.02	0.04	332	1	15	17	12	11	1	295	17	4	33	37	5	15	4	0.5	0.5	0.8	0.2
	4040.05	87.47	1.61	0.41	0.10	4.10	0.26	0.96	0.03	0.02	0.01	95	0	6	10	8	5	1	206	12	2	12	41	3	14	8	0.4	0.3	0.4	0
	4050.00	92.97	2.03	0.60	0.75	1.19	0.31	1.24	0.03	0.01	0.03	804	0	7	14	9	5	1	45	13	3	6	41	5	14	8	0.4	0.3	0.3	0.2
	4060.50	89.70	3.06	0.47	0.72	1.87	0.44	1.81	0.06	0.02	0.03	454	0	7	8	10	5	1	74	17	4	6	35	6	16	8	0.7	0.4	0.8	0.2
	4069.90	95.48	2.41	0.38	0.30	0.60	0.34	1.50	0.03	0.00	0.01	736	0	6	7	10	4	1	49	13	3	2	49	4	13	6	0.3	0.3	0.4	0.2
	4080.10	89.70	2.91	0.30	0.19	2.42	0.42	1.79	0.04	0.02	0.01	509	0	6	5	10	5	1	159	12	3	4	49	5	13	13	0.2	0.3	0.4	0.1
	4090.30	76.60	2.84	0.48	0.83	7.10	0.35	1.60	0.04	0.04	0.03	119	0	7	6	13	5	1	287	10	4	9	34	4	19	9	0.6	0.4	0.6	0
	4100.25	88.89	3.50	0.40	0.78	1.44	0.52	1.97	0.07	0.02	0.03	466	1	8	7	10	4	1	70	10	4	3	87	5	17	11	0.5	0.3	0.8	0.2
	4110.25	88.78	3.53	0.40	0.28	1.80	1.07	2.03	0.05	0.01	0.01	696	2	8	6	11	7	1	129	8	3	3	38	5	15	7	0.2	0.2	0.4	0.1
	4120.20	85.89	4.04	0.39	0.87	2.06	1.01	2.10	0.14	0.03	0.04	775	2	12	7	12	8	1	106	16	8	4	205	9	20	14	0.7	0.4	1.2	0.3
	4130.10	84.03	4.35	0.35	0.70	1.36	2.02	2.24	0.09	0.02	0.02	891	5	11	4	10	8	1	95	12	4	3	45	7	16	12	0.9	0.2	0.7	0.2
	4140.20	81.42	5.96	0.62	1.08	1.63	1.85	2.53	0.22	0.05	0.03	373	5	25	16	14	9	3	66	30	7	8	194	12	20	17	1.7	0.5	1.4	0.6
	4149.70	83.68	7.28	0.71	0.81	0.75	1.36	2.92	0.45	0.09	0.02	480	4	47	13	16	10	4	64	33	15	10	1361	34	79	38	6.0	0.9	2.8	1.2
	4150.00	67.60	13.65	2.01	2.21	1.96	1.26	4.88	0.56	0.14	0.04	436	6	61	11	29	18	11	75	64	15	19	254	27	52	34	3.9	1	2.8	1.4
	4160.00	85.90	4.14	0.54	1.52	2.18	0.59	2.16	0.08	0.04	0.06	825	2	11	11	11	7	2	66	12	6	6	69	8	19	14	0.9	0.5	1.2	0.3
	4170.00	78.62	3.31	0.82	2.50	3.84	0.99	1.78	0.07	0.04	0.10	428	7	9	8	10	16	2	53	10	7	7	45	7	16	12	0.8	0.5	1.4	0.3
	4174.95	78.72	1.06	0.84	3.61	5.66	0.78	0.60	0.02	0.03	0.15	1736	2	5	23	8	7	1	45	5	5	11	43	3	17	25	0.1	0.4	1.6	0.2
	4180.15	88.39	2.60	0.53	1.25	1.82	0.72	1.47	0.05	0.02	0.05	1947	1	9	17	8	5	1	75	7	5	4	64	6	19	3	0.4	0.5	1	0.2
	4190.35	86.02	5.82	0.74	0.71	0.81	1.12	2.68	0.24	0.06	0.02	1075	2	26	18	15	10	4	58	20	9	18	81	17	34	19	2.9	0.5	1.6	0.6
	4199.85	89.57	5.44	0.79	0.18	0.12	0.90	2.97	0.07	0.02	0.00	2548	0	11	16	10	7	1	145	9	4	3	55	7	16	9	1.0	0.4	0.5	0.3
	4210.65	71.58	3.44	1.59	4.05	6.45	0.57	1.74	0.07	0.05	0.15	1477	3	12	19	10	7	3	88	16	12	12	61	7	23	23	1.2	0.7	2.4	0.5
	4217.70	69.08	2.30	1.24	4.77	7.65	0.33	1.14	0.07	0.05	0.16		3	11	18	10	8	2	263	13	15	12	157	7	22	12	2.1	0.8	2.8	0.6
	4230.00	94.82	2.28	0.82	0.12	0.22	0.33	1.38	0.09	0.01	0.00	1535	0	10	17	11	5	1	78	7	4	1	103	6	15	4	0.8	0.3	0.6	0.2
	4240.00	82.32	3.77	1.11	2.09	3.02	0.65	2.05	0.07	0.04	0.07	1493	1	8	13	8	6	2	86	10	10	7	49	7	17	9	1.5	0.5	1.7	0.4
	4250.25	91.92	4.33	0.87	0.17	0.07	0.57	2.46	0.07	0.02	0.00	1279	0	6	17	8	5	1	84	9	4	2	56	7	14	8	0.7	0.5	0.4	0.3
	4260.50	90.91	2.62	0.70	0.51	1.33	0.43	1.56	0.05	0.01	0.01	1239	0	7	15	8	5	1	79	6	4	3	45	5	12	6	0.6	0.3	0.6	0.2
	4270.00	88.27	2.34	1.59	0.48	0.67	2.11	1.19	0.07	0.01	0.03	3640	1	20	39	11	16	1	180	8	4	152	58	6	16	7	0.5	0.4	0.6	0.3
	4280.00	82.49	3.39	1.58	2.04	2.80	0.93	1.66	0.08	0.03	0.08	2923	2	18	17	11	12	2	197	11	9	42	58	8	20	10	1.0	0.5	1.6	0.4
	4290.00	88.30	2.26	1.26	1.03	1.49	1.59	1.21	0.05	0.02	0.04	3555	2	19	29	9	11	1	131	6	6	26	50	6	16	11	0.7	0.4	0.7	0.3
	4300.00	82.16	3.93	1.86	1.16	1.43	2.33	1.79	0.12	0.03	0.04	2813	2	27	15	12	13	3	214	16	7	30	88	10	20	14	1.6	0.6	1.1	0.4
	4310.00	83.78	3.59	1.63	1.25	1.53	1.39	1.66	0.11	0.03	0.04	2470	2	26	23	12	12	3	204	15	8	30	78	10	22	13	1.4	0.6	1.2	0.4
	4320.00	82.58	4.99	2.28	0.66	0.67	3.04	2.18	0.16	0.04	0.03	2617	3	29	26	12	14	3	160	19	7	23	95	13	23	19	1.8	0.6	1.1	0.6
	4330.00	88.25	2.93	1.94	0.47	0.54	1.95	1.40	0.08	0.02	0.03	2653	2	24	26	10	14	2	144	10	4	18	70	8	17	9	1.2	0.3	0.8	0.4
	4340.00	87.85	2.36	1.53	0.87	1.22	2.31	1.19	0.06	0.01	0.04	0	2	24	16	10	13	2	109	7	5	12	63	5	16	14	0.6	0.4	0.8	0.3
	4350.00	82.99	3.74	1.67	0.98	1.39	2.49	1.81	0.09	0.02	0.04	1715	2	19	18	10	11	2	223	9	6	27	67	7	15	4	0.8	0.5	1.2	0.4
	4360.00	80.23	3.30	1.69	0.86	1.34	3.49	1.77	0.08	0.02	0.04	1626	2	19	23	9	12	2	205	8	6	24	67	7	17	10	0.6	0.5	1	0.4
	4370.00	83.05	2.37	1.50	0.72	1.14	3.86	1.28	0.06	0.01	0.03	1177	1	15	28	8	11	1	189	5	5	16	73	5	17	4	1.0	0.4	1	0.3
	4380.00	85.50	2.23	1.58	1.46	2.28	1.21	1.15	0.05	0.02	0.06	1815	2	15	23	8	11	1	150	6	7	15	51	5	16	5	0.9	0.4	1.3	0.4
	4390.00	62.24	1.92	0.91	0.57	0.95	15.92	1.00	0.06	0.00	0.02	3383	1	13	20	9	8	1	119	5	4	18	71	4	14	11	0.4	0.3	0.7	0.2
	4400.00	65.97	1.52	0.84	0.37	0.63	14.15	0.84	0.04	0.00	0.02	0	0	10	19	10	8	1	146	3	3	17	64	3	14	3	0.3	0.3	0.4	0.2

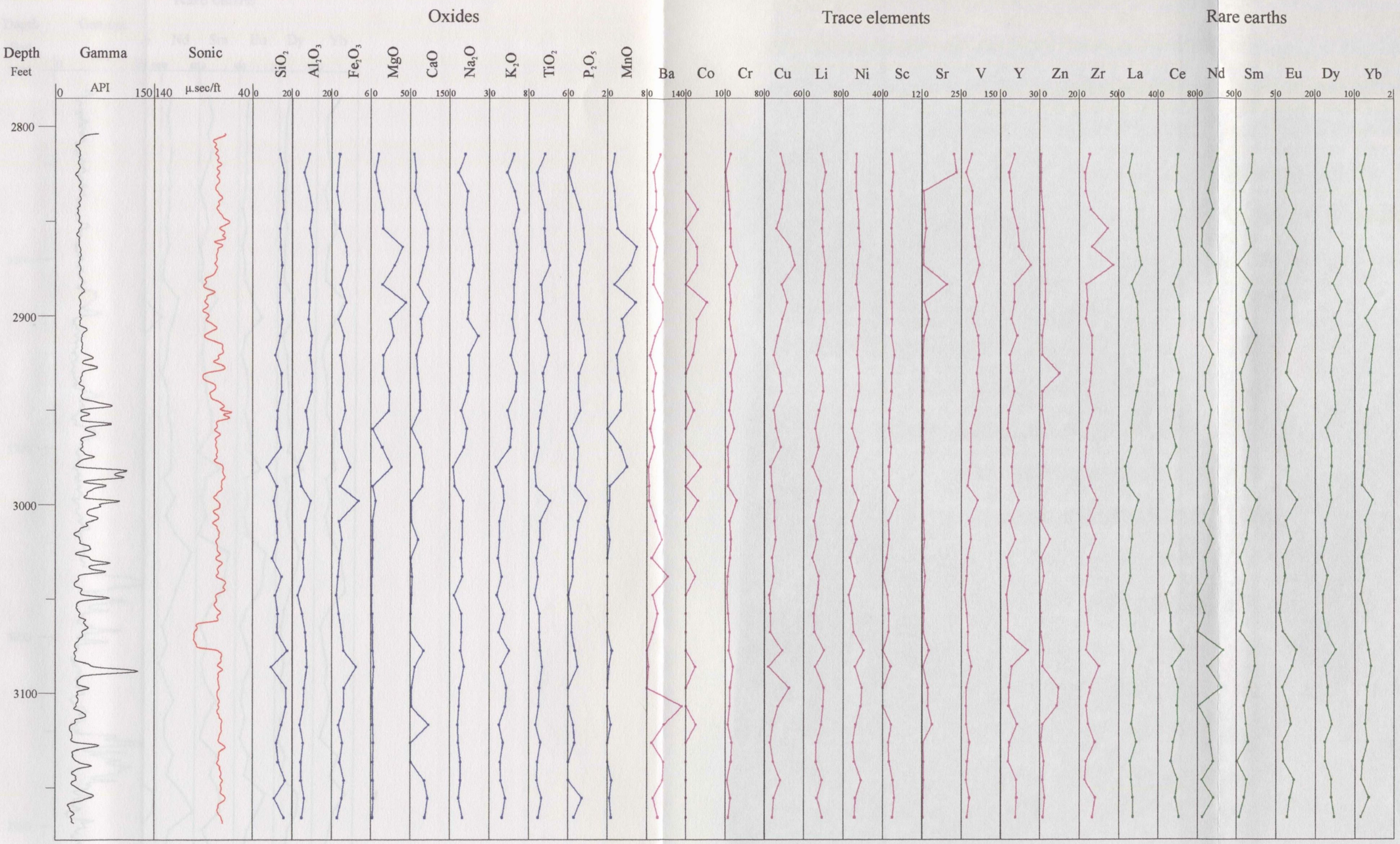
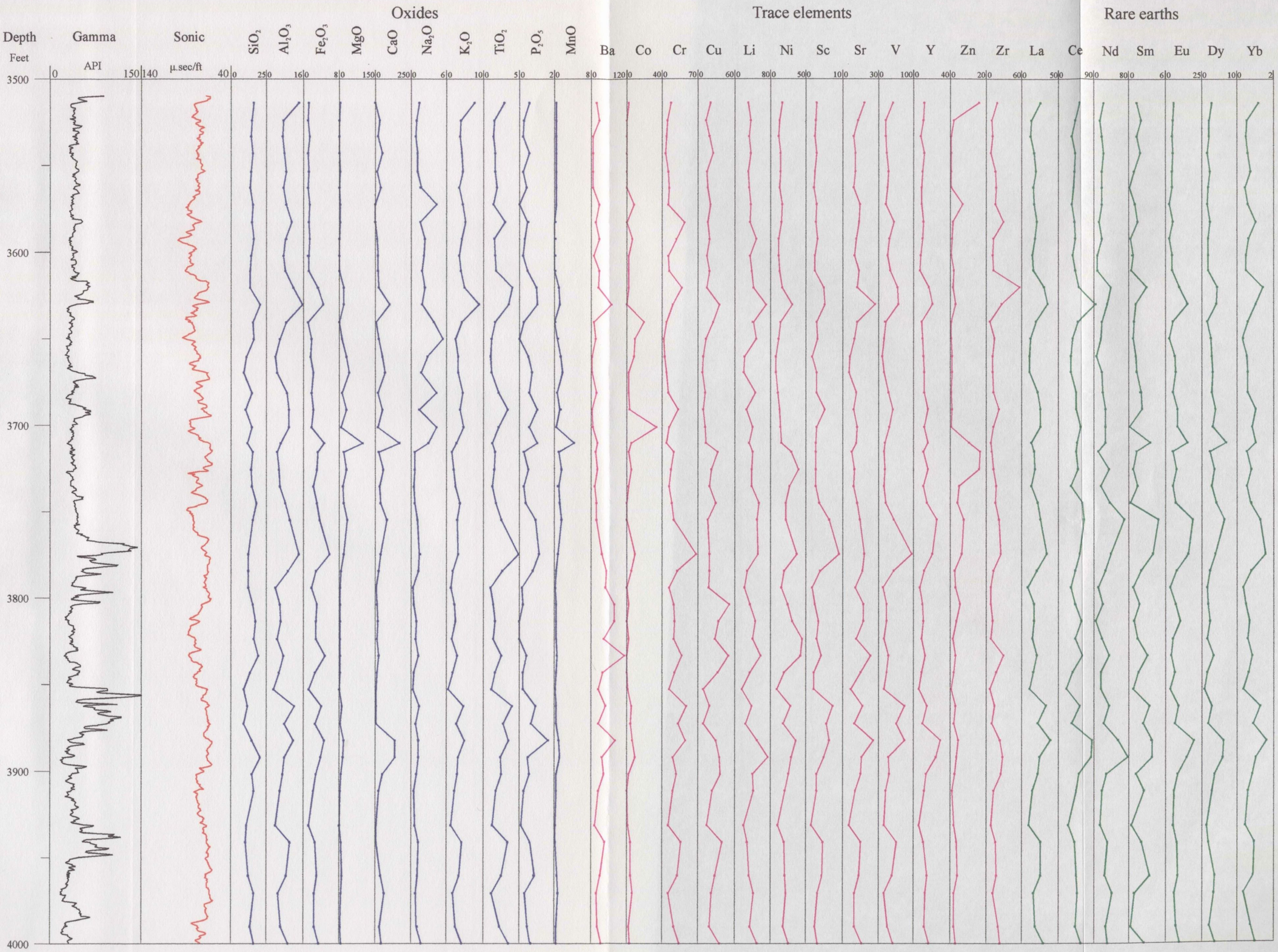
Well 110/2-6: ICP-AES and ICP-MS data (normalised)



Well 110/8a-5: ICP-AES and ICP-MS data (normalised)



Well 110/13-5: ICP-AES and ICP-MS data (normalised)



Well 110/14-3: ICP-AES and ICP-MS data (normalised)