British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

The Scremerston Formation: results of a sedimentological study of onshore outcrop sections and offshore Well 42/13-2

Marine, Coastal and Hydrocarbons Programme

Commissioned Report CR/07/101

BRITISH GEOLOGICAL SURVEY

COMMISSIONED REPORT CR/07/101

The Scremerston Formation: results of a sedimentological study of onshore outcrop sections and offshore Well 42/13-2

N S Jones

Key words

Scremerston Formation, Berwick-upon-Tweed, offshore well 42/13-2, Yoredale Formation, Tyne Limestone Formation, Alston Formation.

Front cover

Channel sandbodies above and below the Dun Limestone at Marshall Meadows Bay, north of Berwick-upon-Tweed.

Bibliographical reference

JONES, N.S. 2007. The Scremerston Formation: results of a sedimentological study of onshore outcrop sections and offshore Well 42/13-2. *British Geological Survey Commissioned Report*, CR/07/101. 70pp.

Keyworth, Nottingham British Geological Survey 2007

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available from the BGS Sales Desks at Nottingham and Edinburgh; see contact details below or shop online at www.thebgs.co.uk

The London Information Office maintains a reference collection of BGS publications including maps for consultation.

The Survey publishes an annual catalogue of its maps and other publications; this catalogue is available from any of the BGS Sales Desks.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Department for International Development and other agencies.

The British Geological Survey is a component body of the Natural Environment Research Council.

Keyworth, Nottingham NG12 5GG

☎ 0115-936 3241 Fax 0115-936 3488
e-mail: sales@bgs.ac.uk
www.bgs.ac.uk
Shop online at: www.thebgs.co.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

☎ 0131-667 1000 Fax 0131-668 2683
e-mail: scotsales@bgs.ac.uk

London Information Office at the Natural History Museum (Earth Galleries), Exhibition Road, South Kensington, London SW7 2DE

☎ 020-7589 4090 Fax 020-7584 8270
☎ 020-7942 5344/45 email: bgslondon@bgs.ac.uk

Forde House, Park Five Business Centre, Harrier Way, Sowton, Exeter, Devon EX2 7HU

☎ 01392-445271 Fax 01392-445371

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS

☎ 028-9066 6595 Fax 028-9066 2835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB

☎ 01491-838800 Fax 01491-692345

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU

☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

Foreword

This report is the published product of a study by the British Geological Survey. The report deals with the sedimentology of the Scremerston Formation at outcrop around Berwick-upon-Tweed and from the offshore North Sea Well 42/13-2.

Acknowledgements

I would like to thank John Rapach of Sterling Resources for commissioning this work, and Colin McGee of Synergy Ltd and Darren McRae of PGL for their kind provision of data to support the study. In addition the PhD research of Andy Gardiner (see Gardiner, 1983) has been used extensively as supporting material for the outcrop study, which is gratefully acknowledged.

Contents

FIGURES

TABLES

Summary

This report describes a study of the Scremerston Formation and lower part of the overlying Yoredale Formation at outcrop and in the onshore subsurface in the Berwick-upon-Tweed area of north-east Northumberland. The work was carried out on behalf of Sterling Resources Ltd and partners, who were interested in the onshore succession as an analogue to similar aged deposits offshore in their area of interest in the North Sea (Quadrant 42 and adjacent areas).

The work was carried out in two phases. Firstly a field-based study of coastal and inland outcrops in the Berwick area was carried out during February 2007. The Scremerston Formation is poorly exposed onshore at Berwick, although the overlying succession, equivalent to the basal part of the offshore Yoredale Formation, is well exposed to the north and south of Berwick. Sedimentologically the Scremerston Formation and lower part of the overlying Yoredale Formation appear similar. The main difference appears to be the occurrence of thick marine limestones in the Yoredale Formation. Hence it is believed that it is valid to include the lower part of the Yoredale Formation within the study.

Overall the succession represents deposition on a delta plain, transitional with a marine setting. Periods of delta advance led to the infilling of marine interdistributary bays. Floodplain and lacustrine facies occur on the delta plain, as well as large braided river channel systems that fed coarse sediment into the basin. The study found that a variety of reservoir and non-reservoir lithofacies characterise the succession. The largest sandbodies consist of stacked major channel systems, up to about 88 ft (27 m) in thickness. These have widths that vary up to about 8 km. Palaeocurrent analysis of the sandbodies show that they have a consistent trend, with sandbodies oriented north-south or north-east to south-west; a southerly or south-westerly flow direction is indicated. The channel fills typically consist of fine- to coarse-grained cross-bedded sandstone, with a high net-to-gross (typically >0.8). Internal heterogeneity, where present, typically comprises beds of floodplain mudstones. These are often discontinuous due to erosion by overlying channels.

The second part of the study involved an analysis of boreholes in the area around and immediately to the south of Berwick. In total 39 onshore boreholes were databased, irregularly distributed across an area of approximately 100 km^2 (~39 square miles). Borehole stick plots were drawn, stratigraphic correlations made and sand-to-non-sand maps were constructed. These sand-to-non-sand maps represent a crude proxy for net-to-gross sand maps and show that, at least onshore, the succession shows significant lateral variability in sand distribution. Schematic palaeogeography maps were compiled for 6 sandbodies within the Scremerston and Yoredale formations. This utilised the borehole and outcrop data.

In addition to this onshore work a visit was made to the Iron Mountain Core Store at Torry, Aberdeen to examine core from Well 42/13-2 (Core 1-3). This report briefly describes the sedimentology of this core and presents a graphical sedimentological log of the well.

1 Introduction

Sterling Resources and partners requested that the British Geological Survey (BGS) carry out a study of the Scremerston Formation at outcrop in north-east England as an analogue to similar aged deposits offshore in their area of interest in the North Sea (Quadrant 42 and adjacent areas). This work was carried out under Contract No. GA/06F/096 (BGS project code E2451R73, under the management of the Marine, Coastal and Hydrocarbons Programme). The original BGS proposal divided the work into three phases (tasks), although only tasks 1-2 were commissioned by Sterling Resources prior to the project commencement:

Task 1. Field-based study of the outcrop sections

It was proposed to spend 5 days carrying out fieldwork examining critical sections of the Scremerston Formation along the Spittal coast south of Berwick and at Lewis Burn, Kielder Forest. Where possible, the following datasets were to be recorded:

- Sandbody dimensional data (mainly thickness)
- Net: gross
- Palaeocurrent data
- Internal architecture and heterogeneity data

Due to the short time period allowed for this task it was decided, with agreement from Sterling Resources, to concentrate the effort on the outcrops in the Berwick area (Figure 1). Fieldwork was carried out in 2 phases: 5-7th February 2007 and 21-22nd February 2007.

Task 2. Borehole Study

The outcrop of the Scremerston Formation continues southwards from Berwick-upon-Tweed for at least 70 km. Within the area immediately to the south of Berwick there are approximately 100 boreholes that penetrate the Scremerston Formation, of which about 70 are shallow holes. These boreholes are typically quite old (drilled about 100 years ago in some cases) and their logs contain variable amounts of information. Nevertheless an initial assessment of these boreholes indicates that there is enough lithological information available in order to estimate net:gross of the succession and to correlate using key marker beds such as limestones and coals. The objectives of this task were to:

- Database the main lithologies of the Scremerston Formation within the deeper boreholes
- Map net:gross in order to gain better 3D understanding of its distribution
- Attempt to correlate these boreholes to try to generate sandbody dimensional data (width:thickness)
- Examine any relevant Coal Authority deep mine abandonment plans and integrate with the borehole data to improve the correlation

Task 3. Integrate data with offshore wells

The purpose of Task 3 was to analyse data from offshore wells and to integrate these results with those from the onshore to maximise their usefulness. The exact details of the work programme for Task 3 could not be finalised prior to the project start date due to a number of unknowns but a provisional outline of work was suggested below:

- Assessment of well logs and core (where available) to identify main channel types, internal heterogeneity, and vertical changes in channel types and stacking patterns
- Analysis of well data to derive sandbody thickness information to produce a width:thickness dataset that could be used for reservoir modelling
- Assessment of borehole image data to gain an understanding of channel trends and thus predict orientation of main sandbodies offshore

It was decided that this phase of work would be reviewed following successful completion of tasks 1 and 2. However, as part of the work carried out during tasks 1 and 2 some of this phase has been accomplished, particularly a study of well 42/13-2. This is described in section 3.

This report documents the results of tasks 1 and 2, together with some data on the results of a sedimentological assessment of Well 42/13-2.

2 Stratigraphy

The Scremerston Formation is a succession of alternating beds of sandstone, siltstone, claystone, coal and thin limestones that is present at outcrop in the area around Berwick-upon-Tweed, north-east England (Figures 1 and 2). The onshore outcrops continue offshore across the western crestal area of the Mid North Sea High and along its flanks eastwards to at least quadrants 39 and 44 (Cameron, 1993). Onshore the stratigraphy of the succession has been recently modified by BGS and is no longer considered to be of formational status (Figure 2), but for the purposes of this report the term Scremerston Formation is retained for ease of comparison with the offshore succession. The characteristics of the formation can be summarised as follows:

OFFSHORE (Cameron, 1993; Collinson, 2005)

- The base is taken at the top of the thick sandstones of the Fell Sandstone Formation
- The top is taken at the lowest marine limestone marked by a high velocity peak on the sonic downhole log; the succession overlying the Scremerston Formation is termed the Yoredale Formation
- The succession is of Late Holkerian-early Asbian age
- The formation typically varies in thickness from 330-1640 ft (100-500 m)
- The formation is characterised by the presence of coal seams (up to 1.5 m/5 ft thick), mudstones, major channel sandstones and thin limestones
- The cyclicity that characterises the later Yoredale Formation is less apparent
- Channel sandbodies are typically up to 66 ft (20 m) thick and are often multistorey
- The formation represents sedimentation on a low relief coastal plain traversed by river channels
- Palaeoflow was broadly to the south

ONSHORE

- The base is taken at the first limestone above the Fell Sandstone Formation
- The succession is Asbian in age
- The formation is approximately 1017 ft (310 m) thick
- The top is taken at the first thick marine limestone, known as the Dun Limestone
- The formation is characterised by the presence of coal seams (up to 2 m/6.6 ft thick), mudstones, major channel sandstones and thin limestones
- The cyclicity that characterises the later Yoredale Formation is less apparent
- Channel sandbodies are typically up to 115 ft (35 m) thick and are often multistorey
- The formation represents sedimentation on a low relief coastal plain traversed by river channels
- Palaeoflow was broadly to the south, but varied from south-west to south-east in the Berwick area, although further south palaeocurrent data indicates flows were to the WSW. It has been suggested that movement along the ENE-WSW trending Stublick-Ninety-Fathom fault belt may have influenced palaeoflow in the hangingwall of the fault in this area (Leeder et al., 1989).

Unfortunately the Scremerston Formation is poorly exposed onshore at Berwick, although the overlying succession (= the upper part of the Tyne Limestone Formation, equivalent to the basal part of the offshore Yoredale Formation, see Figure 2) is well exposed to the north and south of Berwick. The Yoredale Formation is distinguished from the Scremerston Formation by the lower incidence of coals, the occurrence of thick (1-3 m, 3-9 ft) marine limestones and the common development of upwards-coarsening ‘Yoredale’ cycles. Collinson (2005) suggests that offshore the Yoredale Formation is characterised by the development of sandstone-filled palaeovalleys, not seen in earlier units. Study of the lower part of the Yoredale Formation at outcrop (between the Dun Limestone and the level of the Watchlaw Limestone, see Figure 2) indicates that similar facies to the Scremerston Formation are present, with poor development of Yoredale cyclicity. The major difference between the two formations appears to be the occurrence of thick marine limestones in the Yoredale Formation. The regional palaeoflow in the Yoredale Formation is also broadly to the south, similar to the Scremerston Formation. Hence it is suggested that the lower part of the Yoredale Formation can be used as an analogue for the offshore Scremerston Formation, albeit with caution.

3 Well 42/13-2

As part of this study Sterling Resources requested that BGS carry out a brief examination of core from Well 42/13-2 (Cores 1-3, 7383-7506 ft) in order to document the sedimentary facies present and hence determine whether the proposed outcrop study was relevant to the offshore sector. The core material was examined at the Iron Mountain Core Store (Torry, Aberdeen) from 19-20th December 2006. A graphic core log is illustrated in Figure 3 and the details of the sedimentary facies are summarised in Table 1.

3.1 SEDIMENTOLOGY

The detailed sedimentology of the core from 42/13-2 has been described by Gardiner (1997) and further information on the sedimentology and faunas can be found in Riley (1997a, b). Hence the sedimentology is not repeated in detail in this report. Four facies associations are recognised here, divisible into 9 facies types (Table 1). It is clear that the succession represents the deposits of largely terrestrial environments, punctuated by successive marine transgressive events. Lower delta plain, fluvio-deltaic conditions are suggested, with a number of upwards coarsening successions from 5 to 11 ft (1.5-3.4 m) in thickness representing small shoal water and crevasse deltas that filled shallow marine interdistributary bay areas. Periods of bay filling and near emergence were marked by the colonisation of sediment surfaces by plants, leading to soil formation (palaeosol facies association). The marine deposits represent marine flooding events. Unless they were subsequently removed by channel scouring events then they are likely to be fairly extensive and act as baffles, present on a field scale at least.

The dominant facies within the cored interval, forming the reservoir sands, are the channel sands that are present between driller's depths 7442' 3'' – 7492' 10''. These sands are typically fine- to coarse-grained, occasionally pebbly, light grey to brown and well cemented. Pebbles are typically rounded extraformational quartzite clasts, with a few intraformational mudstone clasts. The sands are fairly clean and generally lacking in argillaceous material. The sands are typically cross-bedded throughout, in small sets generally less than a foot in thickness. Small scale upward-fining cycles are present, with the upper part of the succession showing gross overall fining. Marine influence has been recorded in the upper part of the succession. It is clear from the cross-plot of horizontal permeability against porosity that there is a linear relationship between porosity and permeability (Figure 4). The stacked channel facies has the best reservoir properties compared with the other facies present within the cored interval (Gardiner, 1997). Cross-plotting the data for the channel facies only it can be seen that there is a distinct grain size control on reservoir quality, with the coarsest grain sizes having the best reservoir properties (Figure 5).

3.2 CORRELATION WITH OTHER AREAS

3.2.1 Correlation with the onshore succession

As part of this study a generalised vertical section for the onshore succession was constructed, using borehole data. Well 42/13-2 was projected at the same scale and a correlation was attempted (Figure 6). A number of distinct stratigraphic intervals can be defined in the onshore succession, each with a seemingly unique combination of lithological characteristics. These are described, from oldest to youngest, as:

- ***Sand-prone interval*** (Fell Sandstone): This succession, up to 1400 ft thick offshore, comprises channel sands with moderate to high net:gross and interbedded muds.
- ***Mud-prone interval*** (about 380 ft thick onshore): The lowest part of the Scremerston Formation onshore comprises a mudstone-dominant interval with numerous thin coals and limestones. These coals and limestones are typically only a few inches thick so not easily recorded on downhole well logs. Sandstones are generally thin.

- ***Coal-prone interval*** (about 460 ft thick onshore): This interval onshore is characterised by the most numerous and thickest development of coals; numerous coals can also be seen offshore on RHOZ logs. The interval appears to show major upwards-fining, with some channel sandstones, typically more concentrated towards the base of the interval.
- ***Sand-prone interval*** (about 200 ft thick onshore): Numerous thick channel sands characterise this interval. There are also some coals, present both onshore and offshore.
- ***Sand- and limestone-prone interval*** (Yoredale Formation): This interval, about 350 ft thick onshore, is characterised by numerous thick channel sandstones, common marine limestones and rare thin coals.
- ***Sand- and limestone-prone interval*** (Yoredale Formation): This interval, in excess of 360 ft in thickness onshore, forms the upper unit recognised in this study. It is characterised by successive upwards-coarsening 'Yoredale' cycles, some channel sandstones and common marine limestones.

It would appear from an initial appraisal that some of these onshore intervals can be correlated with Well 42/13-2 (Figure 6). However, more detailed study would be required in order to test the validity of this correlation. If it is found that the two areas can be correlated then this would indicate that there was a regional or allocyclic control on sedimentation patterns operating at this time.

3.2.2 Correlation with nearby offshore wells

Sterling Resources also requested that BGS attempt to correlate the Scremerston Formation succession in 42/13-2 with a number of nearby wells. The suggested wells were 41/10-1, 42/9-1, 42/10b-1, 42/13-1, 42/13-2, 42/15a-1 and 42/18-2. A correlation panel showing the proposed correlation is illustrated in Figure 7. Wells 42/9-1 and 42/13-1 are not included in this correlation panel. This is because Well 42/9-1 is not thought to be directly correlatable with the Scremerston Formation and Well 42/13-1 contains a short penetration of Scremerston Formation (about 310 ft) that could not be accurately correlated.

The Fell Sandstone typically forms a good marker succession, comprising a succession of thick channel sands and minor interbedded mudstones. In the Scremerston Formation the lowermost mud-prone interval appears to be correlatable in wells 42/10b-2, 42/13-2 and 42/15a-1 and the overlying coal-prone interval appears to be correlatable in wells 42/10b-2 and 42/13-2. The sand-prone interval can be recognised in both 42/18-2 and 42/13-2; in 42/10b-2 the sand-prone interval contains much less sand and the base is taken at the only significant sandbody in the upper part of the Scremerston Formation. Correlation of the Scremerston Formation appears more problematical in Well 41/10-1, which is considerably more shaly than other wells. The base of the overlying Yoredale Formation is traditionally taken at the lowest marine limestone marked by a high velocity peak on the sonic downhole log (Cameron, 1993; Collinson, 2005). This is not always easy to recognise without carrying out a petrophysical evaluation, however, the overlying Yoredale Formation has a distinctive gamma ray log appearance, marked by regular alternations of sand and shale which form distinctive upwards-coarsening 'Yoredale' cycles. These are best developed upwards from about 200 ft above the base of the formation in wells 42/10b-2 and 42/18-2. The lower part of the Yoredale Formation in Well 41/10-1 appears to be much more shaly than in other nearby wells, possibly indicating that some regional control on sand distribution may have occurred.

4 Field-based study of the outcrop sections

The upper part of the Scremerston Formation and the lower part of the Yoredale Formation is well exposed in coastal outcrops to the north and south of the town of Berwick-upon-Tweed in north-east England. In addition, there are a number of outcrops that occur inland, mainly in former quarries, although these outcrops tend to be of poorer quality (Figure 1). The coastal outcrops to the north and south of Berwick have been extensively studied by Gardiner (1983, 1984) and much of the following section uses material from this research. The sedimentary facies in the Scremerston Formation and lower part of the Yoredale Formation can be broadly grouped as reservoir and non-reservoir, related purely to their original sand content. No other factors were taken into consideration in making this distinction (e.g. later diagenetic modification). The main objective of the field study was to gather data on the main types of reservoir sandbodies present, in order to provide analogue data to better understand the offshore reservoir sandbodies. A detailed sedimentological log of the upper part of the Scremerston Formation and lower part of the Yoredale Formation is illustrated in Figure 8.

4.1 RESERVOIR FACIES

The most important reservoir facies are the fluvial channels. The architecture of these fluvial deposits can be viewed at different scales (Figure 9):

- Channel belt, which represents the whole complex of multistorey and multilateral fluvial channels
- Individual channel bodies, which comprise single channel (i.e. one storey) fills. Individual channels can form ribbons or sheets, depending on their geometry
- Channel elements such as barforms (e.g. lateral and downstream accreting) and bedforms (e.g. trough cross-beds).
- Interchannel elements, such as abandoned channel-fills, crevasse splays or floodplain facies. These are described in the non-reservoir section

4.1.1 Major stacked channel

Typically the largest sandbodies in the Scremerston Formation can be assigned to this facies. This forms the most important facies in terms of its geometry, with sandbodies varying from 40 to 100 ft in thickness (Figures 10 and 11). They generally form tabular sheets (width / thickness >15), typically comprising 2 to 3 individual channel storeys that stack vertically and laterally to form a multistorey-multilateral channel belt deposit (Figure 12). Individual channel storeys are from 15 - 30 ft thick and marked at their base by a laterally continuous undulatory erosion surface (Figures 10-14). Typically, net:gross is high and sandstone comprises 80-90% of the lithofacies. Grain size is quite variable, although they generally comprise medium to coarse-grained sand, which constitute the best reservoir lithofacies. Channel bases (lags) can be coarse to pebbly and channels typically show upwards-fining.

Internally the sandbodies comprise a variety of different scales of bedforms and barforms. The barforms are typically mid-channel and side-attached compound types (cf. Jones and Glover, 2005), which comprise low-angle, inclined bedding surfaces with superimposed small-scale cross-bedding. Also present within the channels are sets of trough and planar-tabular cross-bedding, often forming thick cosets (Figures 15-17). There appears to be little in the way of significant internal lithological heterogeneity in individual channel storeys. Where heterogeneity does occur it usually in the form of floodplain mudstone that is present between channel storeys. The major stacked channel succession present above the Dun Limestone at Marshall Meadows Bay north of Berwick shows good examples of this type of heterogeneity (Figures 10 and 13). Where present, mudstones tend to be a few feet or less in thickness and discontinuous and can be traced laterally for a few hundred feet or less. Their impersistence is related to the presence of overlying erosively-based channel sands which serve to truncate the mudstones.

Palaeocurrent measurements made both by Gardiner (1983) and during this study indicate that these channels flowed towards the south and south-west (see rose diagrams in Figure 8). The low palaeocurrent spread and the general absence of inclined heterolithic barforms, which are more characteristic of meandering channels, suggests that this facies represent the deposits of braided channel systems.

The dimensions of these channel belts are difficult to predict because they depend on the connectedness of a series of separate channel deposits in cross section. Hence individual channel width is not equal to channel belt width, which can be many times greater. Channel length can be considered many times greater than channel width. The palaeogeography maps illustrated in Section 5.1 indicate that the channel widths are generally a few kilometres or more in width.

4.1.2 Major single storey channel

Examples of this facies were present at outcrop at Spittal, south of Berwick, and include the channel above the Dun Limestone, the Skipper Sandstone, the Red Shin Sandstone and the Maidenkirk Brae Sandstone (see Figure 8). The facies comprises single storey, erosively-based sands that vary from 25-40 ft in thickness (Figure 18). The channel-fill generally consists of fine- and medium-grained sandstone; net:gross is high and sandstone typically comprises 85-100% of the channel-fill (Figure 18). Large barforms tend to be lacking and cosets of trough and planar-tabular cross-bedding seem to be dominant, with minor current ripple cross-lamination. The upper parts of these sandbodies are generally upwards-fining. The Maidenkirk Brae Sandstone shows good examples of water escape structures at the top of the sandbody. Palaeocurrents show unidirectional trends, towards the south and south-east.

It was not possible to accurately determine sandbody widths for these sandbodies, although the sandbody that is present below the Dun Limestone present at outcrop north of Berwick has a cross-sectional width of at least 4 km and a maximum thickness of 30 ft (9 m). Gardiner (1983) interprets this facies as the deposits of a series of meandering channels based on the identification of a point-bar in one sandbody. However, the facies is typically sandy, lacks the muddier lithologies that commonly characterise meandering channel systems and the unidirectional palaeocurrent measurements are orientated in a broadly similar direction to those of the Major Stacked Channel facies. Hence a braided river interpretation is favoured here for these single storey channels. It is believed that these form the building blocks to the Major Stacked Channel facies. An example of this is demonstrated by the channel sandstone above the Dun Limestone. To the south of Berwick, at Spittal, it comprises a single storey channel sandbody that is overlain by a thin coal (Figure 8). To the north, at Marshall Meadows Bay, the sandbody at the same stratigraphic level comprises a composite stacked sandbody.

4.1.3 Minor sandy channel

This facies consists of sandbodies that typically range from 8 to about 25 ft in thickness. The facies comprises single storey, erosively-based sands that vary from 25-40 ft in thickness. The channel-fill generally consists of fine- and medium-grained sandstone, rarely up to coarse-grained, and silty sandstone. Sandstone typically comprises 85-100% of the channel-fill (Figure 19). The facies shows high net:gross, although there is a tendency for this facies to be more silty than the major channel facies. However, this heterogeneity tends to occur as silty material draped on cross-bedding foresets rather than as discrete beds (Figure 20). Sedimentary structures include current ripple cross-lamination, small-scale cross-bedding, small-scale scours, convolute bedding and loading, and silty and micaceous carbonaceous drapes. Small coaly or mudstone intraclasts may be present (Figure 19). Large barforms tend to be lacking. The upper parts of these sandbodies are generally upwards-fining and are rooted (Figure 19). Palaeocurrent measurements are largely unidirectional but show a greater degree of variance from the regional trend. For example the minor sandy channel present 65 ft below the Dun Limestone at Spittal has sets of cross-bedding directed towards the north-west (Figure 8).

It was not possible to accurately determine sandbody widths for these sandbodies, although it is thought likely that they are fairly restricted, perhaps only a few hundred feet in width. Sandbodies of this scale are likely to be unconnected and will form discrete ribbon-like sandbodies surrounded by floodplain muds. The palaeocurrent variability shown by this facies suggests that it represents the deposits of meandering channel systems. However, no definitive point-bar deposits were found associated with this facies.

4.1.4 Minor heterolithic channel

This facies comprises erosively-based successions from 6-14 ft thick. The facies typically shows a centimetre to decimetre interbedding of sandstone and mudstone. They generally occur in isolation, although in one example at Huds Head, Spittal [NU 01235 50793] two similar sized minor heterolithic channels were present stacked vertically (Figure 21). The sandstone may range from very fine- to medium-grained and is typically poorly sorted. Sedimentary structures include current ripples, small-scale cross-bedding, convolute bedding and loading, and carbonaceous drapes. Small coaly or mudstone intraclasts may be present. The mudstone is typically silty, with some dispersed sand. Burrowing has also been recorded in this facies. The main feature of this facies is the presence of bedding that is inclined with a slight depositional dip (typically <5°, but up to 20°) at a high angle to the axis of the fluvial channel (as determined by the mean palaeocurrent direction of sedimentary structures within the channel). These inclined surfaces form the major component of the facies and represent the deposits of compound barforms (Figures 22 and 23). They commonly pass laterally into channel abandonment facies, described in Section 4.2.3. Where channel margins have been examined the adjacent lithologies comprise into rooted grey mudstones (grey alluvial palaeosol facies) (Figure 21). Upwards-fining is an important component of this facies. Palaeocurrent analysis shows that these channels are highly variable in flow direction and no consistent trend is demonstrated by the facies (Figure 8).

These heterolithic lithologies are deposited in shallow migrating channels. The interbedding reflects discharge fluctuations in the channel, with mud being deposited during periods of low flow and sand during floods. This type of stratification has been widely described in the literature, where it has been termed inclined heterolithic stratification (Thomas et al., 1987). The beds typically dip towards the channel axis because they have accreted on the inner bank or point-bar of the channel. Their recognition is generally a good indicator of deposition within a meandering channel environment. The two stacked minor heterolithic channels at Huds Head may have formed by the same channel migrating back across the floodplain and cutting into an earlier meander deposit.

Outcrop quality precluded the opportunity to accurately determine sandbody widths for this facies. They are of similar thicknesses to the minor sandy channel facies and hence it is likely that they are of similar dimensions, perhaps tens to a few hundred feet or less in width. Sandbodies of this scale will be mainly unconnected and will form discrete ribbon-like sandbodies surrounded by floodplain muds or they can form complexes of minor channels of limited size. These would form poor reservoirs due to their limited dimensions and their heterolithic nature.

4.1.5 Minor crevasse channel

In the Scremerston Formation crevasse channels are not common, and appear to form heterolithic sandbodies up to about 6.5 ft (2 m) in thickness. They generally comprise fills of siltstone and silty sandstone with low net:gross (typically <0.3). Current ripple cross-lamination is the main sedimentary structure recorded, with some inclined heterolithic stratification; large trough shaped scours are a common feature (Figure 24). Burrowing and rooting have been recorded.

Crevasse channels are formed during flood events where floodwater breaches the bank/levee of the main channel and diverts water and sediment into the floodplain area. The breach represents an area of confined flow termed the crevasse channel. In more distal settings away from the main channel the flow is unconfined and gives rise to crevasse splay deposits. Crevasse channels tend to be laterally restricted (a few hundred metres in width or less) and often show evidence for multiple incisional/scouring events, as a result of repeated flood events. According to Mjøs et al. (1993) crevasse channels have a width/thickness ratio in the range 5-60, with thicknesses up to 23 ft (7 m). In a number of examples in the geological record this facies can be quite sandy and qualify as a reservoir facies (e.g. Fielding, 1986); by definition it will be connected laterally to larger sandbodies. However, those examined from the Scremerston Formation are heterolithic and would probably act as lateral barriers to flow.

4.1.6 Crevasse splay

Crevasse splays form thin, sheet-like beds of very fine- to medium-grained sandstone or silty sandstone. They generally have sharp, flat bases and sharp or upward-fining tops. Individual beds vary in thickness from a few inches up to about a foot and they typically occur interbedded with silty mudstones. In rare instances they can amalgamate to form thicker sandstone deposits, a few feet thick. Current ripple cross-lamination tends to be the dominant sedimentary structure present. They are commonly rooted or occasionally burrowed.

This facies represents the deposits of episodic, unconfined flood events. Individual beds represent fairly instantaneous events that originated from distributary channel systems via crevasse channels. Each bed of sandstone is typically lobate in form and typical deposits range in width and length from tens of feet to a few hundred feet. The low net:gross of crevasse splay successions tends to act as barriers to fluid flow.

4.1.7 Interdistributary bay delta

These comprise upwards-coarsening successions up to 26 ft thick that overlie the marine mudstone facies (Figure 25). Typically they are either overlain by abandonment facies (such as palaeosols) or are eroded into by channels. The lower part generally comprises laminated silty claystone, siltstone and sandy siltstone. Wave-ripple cross-lamination, lenticular lamination and parallel lamination are the main sedimentary structures within the basal part of the facies, with less common current ripples (Figure 26). The lower part is commonly bioturbated, with both *Olivellites* and *Rhizocorallium* recognised (Figure 27). Upwards through the succession the proportion of sandstone increases; the higher parts of the facies usually comprise up to 80% sand. This is generally fine- to medium-grained, often silty and micaceous and typically form laterally extensive sheet-like beds. Siltstone also occurs as thin interbeds. The main sedimentary structures in the upper part of the facies are trough cross-bedding, current-ripple cross-lamination and some wave-ripple cross-lamination (Figure 28). Measured palaeocurrents for this facies appears to be consistent towards the south-west (Gardiner, 1984).

This facies represents small deltas that fed sediment into shallow water interdistributary bays. These bays were obviously marine, as indicated by the presence of underlying marine facies together with the presence of marine trace fossils in the lower part of the delta. The upwards-coarsening indicates progradation of the sediment source, a typical feature of delta advance. Sediment in the lower (prodelta and distal bar) part of the delta was deposited by a combination of suspension and traction load, with reworking of the facies by waves. The upper, more sandy part represents the more proximal part of the delta and is termed the mouth bar. Here the sedimentary structures are dominantly unidirectional and indicate that fluvial processes were dominant. Overlying channels that cut into the tops of deltas could represent feeder channels that fed sediment to the delta front. However, channels that are significantly thicker and coarser than the underlying deltaic deposits are probably not genetically linked.

Gardiner (1983) recognises a number of these interdistributary bay delta deposits and they appear to consistently prograde towards the south-west. It is likely that they would be lobate in form. The interdistributary bay delta present below the Dun Limestone at Marshall Meadows Bay (Figure 29) can be traced laterally in a NW-SE direction approximately perpendicular to palaeoflow for about 3.5 km (c.2.2 miles). This represents the minimum width of this facies at this stratigraphic position. Another example is present immediately above the Dun Limestone and can be examined at both Marshall Meadows Bay and at Spittal. These localities are approximately 7.3 km (c.4.5 miles) apart and probably represent separate mouth bar lobes as part of the same delta system. In both localities the upper part of the delta is erosively truncated by an overlying channel sandstone (Figure 29).

According to classical facies models, mouth bars tend to be cleaner (i.e. less mud), better sorted and coarser in their more proximal parts and thus have the potential to form good reservoirs. However, they can often be quite silty as a function of local conditions operating at the time of deposition, which serves to reduce reservoir quality. The bay deltas examined from the Scremerston Formation appear to more silty and thus reservoir quality would not be as good as the channel sands.

4.1.8 Strandplain/barrier-island facies

This facies is uncommon, but has been recorded at outcrop at Red Shin, south of Berwick [NU 01629 50268], just above the Doupster Oil-Shale (Figures 8 and 30). Here the facies comprises one upwards-coarsening succession, 30 ft thick. As part of this overall upwards-coarsening unit, three sand-prone units are present (marked 1-3 on Figure 8, see section between 400-440 ft), separated by thin (1-2 ft thick) mudstone interbeds (Figure 30). The basal part of the facies comprises silty mudstones that pass upwards into very fine- and fine-grained sandstones via siltstones and silty sandstones. The upper two sandbodies are sharp-based. Wave-ripple cross-lamination is dominant, ripple crestlines trend NW-SE. Minor current-ripple cross-lamination also occurs and there are a number of prominent sets of asymptotically-based cross-bedding also occurs, with foresets dipping towards the WNW (Figure 30). Low-angle bedding surfaces and some small-scale scouring also occur and burrows have been recorded.

This facies has a number of features that make it similar to the interdistributary bay facies, such as its overall upwards-coarsening nature and the common occurrence of wave ripples. However, the presence of lagoonal, rather than open marine, sediments below this facies suggests that it represents some form of coastward migrating barrier system that separated the lagoon from an open marine environment. The lower part of the facies represents deposition in a low energy environment, whilst the upper part represents higher energy, wave dominant conditions. Gardiner (1983) interpreted this succession as a series of NW-SE trending beach barrier or spit complexes, with open water to the south-west and a back bar/lagoonal area present to the north-east. The present work agrees with this interpretation, but uses the term strandplain or barrier-island instead. The trough cross-bedding foresets that dip towards WNW at a low angle to the bar crest are interpreted as small dunes that filled runnels that were cut into the bar crest (Gardiner, 1983). The low angle bedding probably represents bar crest accretion surfaces.

It has not been possible to obtain any information about the geometry of this facies. Gardiner (1983) suggests that this facies forms minor barriers that formed at an interdistributary bay mouth. If this is the case then it is likely to be fairly limited in its extent. The facies would have poor reservoir quality.

4.2 NON-RESERVOIR FACIES

4.2.1 Marine limestone

This facies typically comprise grey to light brown dolomite, limestone and argillaceous limestone in beds up to 6 ft in thickness. They typically overlie coals and floodplain facies (palaeosols) and are normally overlain by marine mudstones (Figure 31). The facies generally contains an abundant marine fauna including brachiopods, bivalves, crinoids, and corals, particularly *Siphonodendron junceum* and *Siphonodendron martini* (Figure 32); *Zoophycos* burrows are also common. The two main limestones in the study interval are the Dun and the Woodend limestones. The Dun Limestone is noticeably erosively-based, removing the underlying Dun Coal along part of the exposed outcrop at Huds Head, Spittal. These limestones are fairly extensive in their distribution, being correlated across large areas of Northumberland (thousands of square kilometres) (Frost, 1969).

This facies represents the deposits of the early part of a marine transgression (transgressive systems tract), deposited in fully marine conditions. Transgression is likely to have been rapid, allowing the waves to cut a scour surface (often referred to as a ravinement surface or a transgressive surface of erosion); this is shown by the erosive contact between the Dun Limestone and the underlying coal. It is likely that the limestone was deposited as a result of the shut-down of clastic supply into the basin, following extensive marine flooding of the continental area. It is likely that this facies would act as a seal and, given its extensive distribution, would be basin-wide.

4.2.2 Marine mudstone

These sediments are predominantly dark grey to black, organic-rich claystones and silty claystones in units up to a few feet in thickness (Figure 33). Thin siltstone and very fine-grained sandstone laminae also occur in places. The mudstones contain a marine fauna including brachiopods, bivalves and crinoids, with rare corals. Siderite nodules and thin beds are also present (Figure 33). The facies usually form units a few feet in thickness, up to about 10 ft, often capped by upwards-coarsening cycles. Where silty and sandy laminae are present the facies can often be seen to be bioturbated, with *Arenicolites*, *Diplocraterion*, *Rhizocorallium* and *Olivellites* recorded.

This facies was deposited during periods of marine transgression. They probably formed under low-energy conditions, probably associated with slow depositional rates. In the subsurface such units may form field-wide seals that can be recognised by their pronounced high gamma-ray peaks. Where these mudstones were deposited following important glacio-eustatic sea-level rises they are likely to be present on a basin to global scale. However, not all these mudstones will represent such events; some will merely represent more localised interdistributary bay deposits. These more local facies are probably characterised by passing upwards into upwards coarsening successions, which represent interdistributary bay deltas. These mudstones would probably be continuous at a field-scale but would not be regional markers.

4.2.3 Channel abandonment facies

The upper parts of channel facies commonly show upwards-fining, and consist of interbedded sandstone and mudstone capping the fluvial channel (Figures 19 and 29). Alternatively they may consist largely of mudstone within large lenticular channel forms (Figure 34). They may occur at the top of a single storey fluvial channel or can occur at several levels within a multistorey fluvial channel. These abandoned channel successions can be up to 20 ft in thickness in places. The more heterolithic deposits show a centimetre to decimetre interbedding of sand and mud, with poor sorting and low overall net:gross (typically less than 0.3). The beds typically dip towards the channel axis and form inclined heterolithic stratification. Notable features include current ripple cross-lamination, small-scale cross-bedding, convolute bedding and loading, carbonaceous drapes and burrowing (Figures 35 and 36). Soft-sediment deformation is a common feature, with overturned or rotated slump units sometimes recognised (Figure 34).

These heterolithic lithologies are deposited in the abandoned parts of migrating channels. The mechanism of channel-filling depends on the rate of channel abandonment. Gradual abandonment results in a classical upwards-fining character as flows became gradually more restricted. The fine grain size and small bedforms indicate a reduction in flow velocities as the sediment supplied to the channels became more restricted. The interbedding reflects discharge fluctuations in the channel with mud being deposited during slack water periods and sands during floods. The inclined heterolithic stratification represent point bar deposits accreted on the inner bank of the channels. Rapid abandonment results in a complete switch off of flows into the channel, with the abandoned channel reach usually filling with mud. Soft sediment deformation and slump structures are indicative of instability within the abandoned channel, with slumping representing bank material that collapsed into the abandoned channel reach.

These deposits are likely to be curvilinear in form as a result of deposition in meandering channels and are likely to have restricted widths (a few tens to hundreds of feet). Their effective vertical permeability is restricted because of the interbedding with mudstones and hence would act as baffles to vertical flow either at the top or within the otherwise very high quality fluvial channels.

4.2.4 Floodplain-palaeosol facies

A palaeosol, as defined here, represents an ancient, preserved, *in situ* buried soil formed during a period of non-deposition and pedogenic (soil-forming) processes. Typically, their main characteristics are the partial or total destratification of the host lithology as a result of pedogenic processes (roots and burrows), the presence of distinct horizonation, varied colouration or mottling, the presence of roots, leaching or eluviation of material and precipitation of concretionary nodular material.

Calcretes: These form beds up to 5 ft in thickness composed of carbonate nodules in a matrix of sediment. Nodules have been found to comprise ferroan dolomite micrite (Gardiner, 1983); they are irregular subspherical and vein like and often coalesced into larger masses (Figure 37). They are typically oriented subvertically and on top surfaces form polygonal shapes. In rare instances places roots can be seen.

These horizons are believed to represent calcrete palaeosols and are interpreted to be of pedogenic origin. The carbonate grew as nodules (glaebules) in a soil that was subject to intensive evapo-transpiration of carbonate saturated pore waters. The muddy matrix of this facies was probably deposited by overland subaqueous flows, but later pedogenic processes have significantly modified the deposit. The presence of desiccation cracks indicates well-drained conditions were prevalent. The glaebules form by the displacive growth of calcium carbonate in the vadose zone of the soil (Wright and Tucker, 1991). The presence of roots and desiccation cracks also support the palaeosol interpretation and points to a period of subaerial emergence of the sediment surface. The presence of this type of palaeosol is generally taken as an indicator of formation in a semi-arid climate and the relatively low PCO_2 in arid and semi arid soils is now thought to be a significant contributory factor in the precipitation of calcium carbonate (Marion et al., 1985). It is clear that the climate must have been cyclical; calcretes passing upwards into grey beds record the transition from semi-arid to humid conditions.

Grey alluvial palaeosol: These typically comprise grey mudstone successions a few feet in thickness. They can be laminated to structureless, with a few roots present and sporadic siderite concretions; these can form large vertical concretionary structures up to 2 ft long (Figure 38). Burrows have also been recorded in this facies.

The facies represents the deposition of mud from weak subaqueous flows, probably by overbank flows from nearby channels. The grey coloration indicates that waterlogged, reducing conditions were prevalent and the presence of roots indicates that the sediment surfaces was colonised by plants. The relatively minor amounts of rooting associated with this facies indicates fairly regular sedimentation on an actively aggrading alluvial plain which reduced the amount of pedogenic modification. Alluvial soils are immature and are commonly developed on modern day alluvial and deltaic plains close to rivers where they are often flooded.

Gley palaeosols: This type of palaeosol is characterised by grey to dark grey brown claystone, silty claystone and siltstone in beds up to about 8 ft in thickness (Figure 39). The presence of abundant rooting, including *Stigmaria*, is a common feature of this facies. These contain abundant listric surfaces, which are small-scale curved and slickensided surfaces. Other features include partially or completed oxidised siderite concretions; these commonly form around root channels to form rhizocretions; in places these are oxidised to hematite.

This type of palaeosol is interpreted as a gleysol that originally accumulated under poorly-drained (waterlogged), reducing conditions. The grey colour is an indication of the ferrous state of iron and the preservation of organic material, both indicative of reducing conditions. The preservation of common roots, including *Stigmaria*, also support a waterlogged setting. Listric surfaces are thought to have formed by the compactional reorientation of clay minerals associated with the presence of organic debris (Schiller, 1980); they are typically characteristic of poorly drained soils (Guion et al., 1995). The presence of relict siderite nodules partially replaced by hematite indicates a formation originally under reducing conditions and later replacement as a result of oxidation.

Coal: These form beds of coal or shaly coal (Figure 39) typically less than about 1.6 ft (0.5 m) in thickness, although the thickest coal in the district (Scremerston Main Coal) can be up to 6 ft (1.8 m) or more in thickness, albeit with mudstone interbeds. Borehole data indicates that the coals are highly variable in terms of their thickness and siliciclastic content laterally.

Coals are interpreted to have formed from the autochthonous deposition, burial and coalification of organic material. This organic material formed in shallow, submerged peat-forming mires which developed on abandoned channels and on infilled sediment surfaces. The interlaminated or interbedded mudstone represents sediment brought into the mire during floods. The variable nature of these coals is more indicative of formation in a lower delta plain environment. Coals in the UK typically have low permeability (<0.001 mD) and hence intact thick coals can form pressure seals and/or barriers to fluid flow.

4.2.5 Lacustrine facies

Lacustrine facies are well developed in a 13 ft (4 m) thick succession exposed on the coast at Red Shin [NU 01663 50261]. The succession comprises a lowermost lacustrine limestone (‘cementstone’), overlain by grey mudstone, then an algal bed and an oil-shale (=Doupster Oil-Shale) (Figure 8). The lacustrine limestone comprises a thick bed of ferroan dolomite micrite, containing a restricted fauna of ostracods and probable fish fragments (Gardiner, 1983) (Figure 40). The upper surface is uneven and contains polygonal cracks. It is overlain by a 6.5 ft (2 m) thick succession of green illite-rich mudstone with a 1.6 ft (0.5 m) algal bed at its top (Gardiner, 1983). The algal bed contains abundant spherical and elliptical oncolites, each typically 4 cm across (Figure 41). They have an uneven, pustular form and internally they are concentrically laminated. Thin sections indicate that they comprise dark micrite laminae with some clay and fine silt laminae (Gardiner, 1983). The top of the oncolite bed contains fish fragments (Gardiner, 1983). Overlying the oncolite bed is a 3.2 ft (1 m) thick succession of dark grey mudstones including the Doupster Oil-Shale (Figure 41). This comprises a 0.3 ft (0.1 m) thick, dark grey to black, well-laminated mudstone containing ostracods and fish fragments.

This entire succession is interpreted as lacustrine. The cementstone was probably deposited in a shallow floodplain lake of limited lateral extent. It may have undergone some pedogenic modification (Gardiner, 1983). The oncolite bed is interpreted to be algal in origin. The oncolite grains form as mucilaginous layers, rich in blue-green algae. Onto this the micrite is thought to have been deposited as a precipitation of carbonate related to the decay of the organic mucilage (Leeder, 1975). The clay and silt probably adheres to the outside of the grain. The rounded form indicates movement of the oncolites and points to deposition in a body of water. Modern oncolites occur in marine, lagoonal and lake environments. The general absence of marine fauna associated with this succession suggests that they are not fully marine, thus suggesting either a lagoonal or lake origin for the algal bed.

Gardiner (1983) suggests that the oil-shale at the top of the succession may represent an interdistributary bay deposit, or possibly a lagoonal deposit. Oil-shale deposits are well known from the Asbian-Brigantian West Lothian Oil-Shale Formation of the Midland Valley of Scotland. Here they have been interpreted as algal oozes that formed in shallow, stratified lakes characterised by anaerobic bottom conditions (Parnell, 1988). These are thought to be ephemeral lakes, with maximum organic productivity during permanent or highstand lacustrine phases.

The fine-grained nature of these facies indicates that they are likely to form barriers to fluid flow. However, this would be a function of their continuity and it is thought likely that these facies are likely to be fairly restricted in distribution, although borehole data indicates that the Doupster Oil-Shale can be recognised over a NE-SW distance of at least 5 km.

The sedimentary facies described in this section represent deposits on the lower part of a delta plain and the adjacent marine environment. The repeated advance of fluvial systems sourced from the north and north-east led to the deposition of a series of prograding, upwards-coarsening successions as shallow interdistributary bay areas were infilled. These were predominantly river-dominated systems, although a strong wave influence resulted in the reworking of parts of these deltaic deposits. Coastal plain and lacustrine environments formed behind the coastline. These environments are marked by the deposition of muddy facies, although coals and fresh-water limestones (cementstones) are also present. Large sandy braided river systems also occur, carrying a coarse sediment load towards the south and south-west. These probably formed either in response to tectonic uplift in the hinterland or to falling sea-level and lowstand conditions.

Periods of sea-level rise were marked by the flooding of these coastal plain deltaic systems. Limestone commonly forms the lower part of these marine successions and typically these can be correlated over several thousand square kilometres. This clearly indicates the switching off of the clastic sediment system as the continental environment was drowned. A high-magnitude and high frequency glacio-eustatic mechanism is favoured for these marine flooding surfaces (Hampson et al., 1997). Wright and Vanstone (2001) suggest that the Asbian to early Brigantian sea-level oscillations were of the order of between 10-50 m, reaching up to 95 m by late Brigantian times and the average cycle periodicity is though to approximate to the 100-120 ka eccentricity band. The overlying marine mudstones probably represent sea-level highstand deposits, formed as clastic systems re-established themselves and fed muddy sediment out across the shelf.

5 Onshore borehole study

This part of the study involved analysing, databasing and correlating the main onshore boreholes within the Berwick area. Two outcrop sections were also recorded in the database. In total 39 onshore boreholes were databased, irregularly distributed across an area of approximately 100 km^2 (~39 square miles) (Figure 42). Typically all boreholes over about 100 ft (~30 m) in length were used in this study. The boreholes varied considerably in vintage and quality, with many drilled as coal exploration boreholes during the main phase of mining in the area in the late 19th century. The main aims of the borehole phase of the study were:

- To produce palaeogeography maps showing the distribution of channel sands during certain stratigraphic intervals
- To produce net:gross sand maps to better understand the distribution of sand. This would be potentially useful as an analogue to understanding the variations seen offshore

Data from the boreholes is of varying quality so to ensure consistency of databasing 5 main lithotypes were recorded: these are coal (coal), limestone (lmst), claystone/mudstone (mdst), sandstone (sdst) and siltstone (slst). In addition the top superficial layer (mainly till and soil) was also databased (marked as ‘drftu’ in the database). These were input into an Oracle database (BGS_Borehole_Geology) and subsequently exported to MS Excel; the database is included on the CD-Rom included with this report. Important stratigraphic marker beds were also recorded in the database. These generally consist of named coals and limestones and in some cases the thicker sandstones. Where the stratigraphy is not marked on the borehole logs it was determined using a combination of BGS geological maps, the areas of known worked coals and by correlation with nearby boreholes.

Following databasing a graphical stick log was produced for each of the 39 boreholes and outcrop logs. Stratigraphic borehole correlation panels were then constructed for 3 stratigraphic intervals:

1. Fell Sandstone to Bulman (Main) Coal
2. Bulman (Main Coal) to Dun Limestone
3. Dun Limestone and above

These are illustrated in Figures 43 to 45. The borehole correlation panels show that vertical and lateral lithological variability is the norm within the Scremerston Formation, at least in the onshore succession. The named coal seams can usually be correlated for significant distances inland, these tend to be the thickest and most commonly worked coals. The position of former underground coal workings can also be used to confirm the stratigraphy and hence the correlation inland. Limestones tend to be thin and impersistent in the Scremerston Formation, but are more common in the overlying Tyne Limestone and Alston formations (equivalent to the offshore Yoredale Formation), where they can be used for correlation purposes. The thicker sandbodies could generally be correlated for large distances (many kilometres), indicating that they are probably large ribbons (width/thickness <15) or more probably sheet-like in form. Outcrop examination supports the interpretation that these major sandbodies represent channel facies. In most instances it was not possible to correlate the thinner sandbodies; this suggests that they form small, probably narrow sandbodies.

5.1 SCHEMATIC PALAEOGEOGRAPHICAL MAPS

Once the major sandbodies were identified simplified palaeogeography maps were then produced. The aim behind the construction of these maps is to illustrate the channel facies and hence gain a better understanding of the geometry of these sandbodies. Production of these maps is limited by a number of factors, particularly the quality, spacing and total depth of the boreholes and this makes it difficult to correlate the smaller sandbodies in the succession. Hence the sandbodies chosen tend to be the thickest and most extensive so there is an inherent bias in these maps towards the largest channel sandbodies in the succession. Further east and south-east, where the overlying cover of Tyne Limestone and Alston formation rocks is thickest, there are fewer deep boreholes and hence there is less data to support the production of the palaeogeography maps (Figure 42). The sandbodies chosen for mapping are shown in Figure 46.

Palaeogeography maps were overlain on a backdrop showing the coastline, the outcrop of the Scremerston Formation and the line of the River Tweed. Boreholes used per map are coloured red, those that did not penetrate the relevant sandbody are coloured purple. The relevant borehole stick logs are pasted onto each map, with only the appropriate stratigraphic part of each borehole shown. Detailed BGS geological maps (‘field slips’) were also examined to identify the known (mapped) positions of sandbodies at surface for input into the palaeogeography maps; where applicable these mapped sandbody positions are shown on the maps as points. Finally, palaeocurrent data is also shown on the maps if available. After compilation of all the data an interpretation of the likely channel trends and widths were constructed. In total 6 palaeogeography maps are illustrated in Figures 47 to 52. It should be stressed that these maps are highly speculative and schematic and, in many instances, there is not enough data to accurately constrain their margins. In addition, in most cases, these channels actually represent channel belt deposits rather than individual channel-fills. It can be seen from these maps that channel widths and thicknesses vary considerably. It is likely that these larger sandbodies are low sinuosity-braided in form.

The large fluvial systems that characterise the Fell Sandstone show flow directions towards the south and south-west (Turner & Monro, 1987) and it is clear from the palaeocurrent data collected by Gardiner (1983), and confirmed by this study, that the regional palaeoflow for the Scremerston Formation in the Berwick area was also in the same direction. Offshore, the work of Maynard and Dunay (1999) for the Whitby Member of the Scremerston Formation also show similar palaeocurrent trends. The main source of sediment supply into the North Sea and onshore UK during both the Dinantian and the Namurian is thought to be the Laurentian and Baltican shield areas to the north of Britain (Cliff et al., 1991; Collinson, 2005). This carried predominantly quartzo-feldspathic sediment into the basin via large southerly flowing river systems. It would seem sensible to conclude that the Scremerston Formation forms part of this large Pennine river system. Hence where there was little or no palaeocurrent data available from outcrop studies to constrain the trend of channels in the Scremerston Formation a southerly to south-westerly trend was used on the maps.

The sandbodies for which palaeogeography maps have been drawn are discussed in the following section.

5.1.1 Ten-Quarter Freestone

This is the name for the sandbody that occurs in the succession immediately above the Three-Quarter Coal (Figure 46). This sandbody is exposed along the A1167 road south of Berwick, near the Springhill Reservoir [NU 00082 50654]. The sandstone forms a near continuous outcrop dipping at approximately 16° towards the south-east; the exposed sandbody is approximately 41 ft (12.5 m) thick (Figure 14). A further 18 ft (5.5 m) thick sandbody occurs 22 ft (6.6 m) above the main sandbody, separated by a grassy area of no exposure. The lower sandbody comprises medium-grained, trough cross-bedded sandstone. The few palaeocurrent measurements taken indicate flows to the WSW. A number of internal erosion surfaces are present suggesting that this represents a system of stacked channels. There are common soft sediment deformation structures, mainly in the form of convolute lamination and dewatering structures. The upper part of the sandbody has clay-lined cross-bedding foresets and is burrowed (Figure 14). This may represent a marine influence in the top of the sandstone. If this is the case then this is similar to the main reservoir sandbody in Well 42/13-2.

The palaeogeography map for this channel shows a large channel system that fed sediment towards the south-west (Figure 47). This flow direction is supported by limited palaeocurrent data from the A1167 road outcrop. In the Berwick area the channel belt is approximately 3.5 km in width although there is little constraint on the positions of both sides of the channel belt so it should be taken as a minimum width. Rapid lateral changes are indicated by the abrupt change from channel facies in the Felkington Old Pit borehole to non-channel (?floodplain) facies in the Shoreswood Colliery borehole. The channel belt is a maximum of 51 ft (15.5 m) thick, proved in boreholes. To the south-west the channel belt splits into two distributaries, although there is no data to support this. A further channel belt is drawn around the Heston No.1 borehole in the south. The rationale behind this is that it is felt unlikely that a channel belt of this thickness would occupy a channel belt width in excess of 14 km and it would therefore be more sensible to show the sandbody as a series of narrower distributaries.

5.1.2 Bulman Rock

This is the name for the sandbody that occurs in the succession immediately above the Bulman Main Coal (Figure 46). The Bulman Rock is not present at outcrop but has been recorded in a number of boreholes in the Berwick area (Figure 48). It forms a sandbody with a maximum thickness of 115 ft (35 m) and is likely to represent a major stacked channel. The palaeogeography map for this channel shows it to comprise one low sinuosity channel belt (Figure 48). There is no palaeocurrent data available so a general south-westerly trend is taken. The boreholes that prove the sandstone generally show thick sandstones just above the top of the Bulman Main Coal. In the Murton Colliery borehole the sandstone is high in the succession, occurring not far below the base of the Scremerston Main Coal. It is suggested that this represents the higher part of an upwards-coarsening deltaic succession, although it could equally be a later channel. The north-westerly margin of the major channel system can be reasonably well located from borehole data, however, the south-easterly margin is inferred. It is taken as roughly equidistant between the Ford Moss borehole, which proves channel belt facies, and the Heston No.1 borehole, in which channel sands are absent. This gives a channel belt width of approximately 8.5 km.

5.1.3 Scremerston Main Rock

The Scremerston Main Rock is the name given to a sandbody that occurs above the Scremerston Main Coal (Figure 46). It is present at outcrop in two small disused quarries south of Berwick ([NU 00893 50023] and [NU 00708 50944]) and at Catchlaw Crag [NT 99733 49671]. It typically comprises fine- and medium-grained, trough cross-bedded and ripple cross-laminated sandstone. Palaeocurrents are variable, directed towards the south-east, south and south-west (Figure 49). Convolute lamination is common in one former quarry [NU 00708 50944]. A maximum of 26 ft (8 m) of sandstone is exposed at outcrop, although boreholes indicate that the sandbody is perhaps in excess of 41 ft (12.5 m) in thickness (Felkington Old Pit borehole). The borehole data indicates that there is common lateral variation between adjacent boreholes, with thin channel sandstones and common floodplain facies noted. Hence it is suggested that the channel belts were not very wide. Two fairly narrow channel belts are represented on the palaeogeography map in Figure 49. These generally trend north-east to south-west and are curvilinear in form. Channel belt widths are inferred to be up to a maximum width of 3.5 km, although there is not good constraint on the positions of their margins.

5.1.4 Robie's Sandstone

This is the name for the sandbody that occurs in the succession immediately above Robie's Coal (Figure 46). It is present at outcrop at The Cutting Strip near Scremerston [NU 00941 49118], where it forms discontinuous exposures along the side of a former mineral (coal) railway. The sandbody is approximately 80 ft (24 m) thick here and comprises trough cross-bedded, medium-grained feldspathic sandstone. Towards the base there are beds of coarse and granular sandstone and grey mudstone intraclasts also occur. Cross-bedding measurements indicate a unidirectional flow towards the south (Figure 50). The upper part of the sandbody becomes thinner bedded and shows slight fining. Exposures of the Robie's Sandstone are also present at Lamberton Beach, north of Berwick, where an erosively-based, medium-grained, cross-bedded sandstone occurs, 46 ft (14 m) thick (Gardiner, 1983). Palaeocurrents are directed towards the south-west (Gardiner, 1983).

A sandbody is also present on the foreshore at the base of the succession at Spittal which appears to be at or close to the same stratigraphic level as this sandbody. However, this sandbody, 16 ft (5 m) thick, is finer-grained, and more silty (Figures 19 and 20). Palaeocurrents for this sandbody are directed towards the north-west (Figures 8 and 50). If this is the same channel system as that present at The Cutting Strip then it might suggest that the channel is meandering in form. However, the differing grain size, sandbody thickness and palaeocurrent directions suggests that it might not be the same sandbody. Alternatively there might be a number of sandbodies present at this stratigraphic level that stack to produce a fairly extensive channel belt sandbody.

Assuming that the sandbodies at The Cutting Strip and Lamberton Beach form part of the same channel belt complex this gives a channel belt width of at least 8.5 km (Figure 50). There is no constraint on the northern margin of the channel belt and poor control on the southern margin, so it is likely that the belt was even wider. Boreholes indicates that the channel is a maximum of 92 ft (28 m) thick. Flow direction of the channel belt is interpreted to be towards the south-south-west.

5.1.5 Sandstone below Dun Limestone

The sandstone below the Dun Limestone is present at outcrop at Marshall Meadows Bay, north of Berwick (Figure 29). It comprises a fine- to medium-grained, erosively-based sandstone, 30 ft (9 m) thick. The upper 11-13 ft (3-4 m) fines upwards and comprises channel abandonment sands and silts (Figure 29). The main bulk of the sandbody is cross-bedded, with current ripple cross-lamination in the upper, finer part. Palaeocurrent data indicates flow was directed towards the south-south-west and south-west (Figure 53). Outcrops suggest that it represents one single storey channel fill rather than a channel belt. Borehole data provides reasonable constraint on the dimensions of the channel, at least in the Berwick area, and it would appear to form a fairly restricted channel deposit, up to a maximum of about 3.2 km in width, trending roughly north-south (Figure 51). The margins of this channel are marked by the presence of channel overbank and floodplain facies at Spittal (Figure 21). Ancroft 1 and Scremerston 2 boreholes also form a constraint on the channel width, narrowing it to about 2 km. A 52 ft (15.7 m) thick sandbody is present in the Heston No.1 borehole in the south of the study area (Figure 51). If this can be correlated with the sandbody at Berwick then gives a minimum length to this sandbody of at least 26 km.

5.1.6 Channel above the Dun Limestone

The stacked channel sandbody that occurs above the Dun Limestone is well exposed on the coast around Berwick, both to the south at Spittal and north between St John's Haven and Lamberton Beach. The sandbody has been described by both Gardiner (1983, 1984) and Maynard & Dunay (1999). Maynard & Dunay (1999) term this sandbody the Redshin Quarry Sandstone and suggest that it is an onshore analogue for the offshore Whitby Member sandbody. The name Redshin Sandstone is incorrect because the sandstone that is present at Redshin Quarry occurs at a much higher level in the stratigraphy, immediately below the level of the Watchlaw Limestone (Figures 1 and 8). Maynard & Dunay (1999) suggest that this is a composite sandbody formed from a number of separate channels that stack vertically. Internally the sandbody predominantly comprises planar-tabular cross-bedding. A sheet-like, braided fluvial sandstone is proposed for this sandbody on the basis of its width (in excess of 9 km) and its length, which is greater than 60 km (Maynard & Dunay, 1999). They stress the importance of the recognition of macroscale and mesoscale architecture of the sandbody, particularly the observation that channels are lined by fines (mudstones). They point out that were similar features to be recognised in an offshore setting they could affect production (Maynard & Dunay, 1999).

Immediately above the limestone is a coarsening-upwards succession (interdistributary bay delta); this is truncated by the multistorey channel sandstone, which cuts down to within 1 ft (0.3 m) of the limestone locally (Figure 53). Between St John's Haven and Spittal (a distance of 6 km) the sandbody has a relief of about 30 ft (9 m) on its basal erosion surface. The sandstone is up to a maximum of 88 ft (27 m) thick in Marshall Meadows Bay. The sandbody is clearly multistorey, with channel bases marked by the recognition of laterally persistent erosion surfaces (Figures 10-13). Gardiner (1983) reports that these erosion surfaces can be traced for between 230 and 1970 ft (70 and 600 m), exceptionally up to 3280 ft (1000 m). The tops of channels can be defined by mudstone beds, representing either low flow channel deposits or floodplain facies. These can be a few feet in thickness, although they are typically truncated by the erosion surfaces of overlying channels (Figures 10 and 13). Grain size appears to be quite variable, varying from fine- to coarse-grained and pebbly locally. The coarser grain sizes appear to be concentrated in the lower parts of channel storeys and appear to be more common in the uppermost channel storeys in the Marshall Meadows Bay area. The lower sandbodies typically comprise fine- to medium-grained sandstone. Trough and planar-tabular cross-bedding form the most important in-channel elements, although low-angle mid-channel barforms with superimposed cross-bedding is also a feature in places (Figure 12). Palaeocurrent data indicates that the flow direction was towards the south-west.

At Spittal the succession differs slightly from north of Berwick in that the lowermost 30 ft (9 m) of sandstone comprises a single storey channel that is overlain by an inferior coal. The base of this channel is lined by burrows suggesting that it fed sediment into a marine environment (Gardiner, 1983). It may be that this channel represents a smaller distributary system that pre-dates the later multistorey channel system (Gardiner, 1983). Elsewhere channel sands cut down to just above the Dun Limestone and the reality is, from a hydrocarbon reservoir viewpoint, that this sandstone at Spittal must occur adjacent to these and hence form part of a multistorey-multilateral sandbody system.

The thickness and multistorey nature of this sandbody indicates that this is not a small distributary channel but represents a major braided river system that fed sediment into the basin towards the south-west. The sandbody was built up from numerous broad, lenticular sandbodies which represent a series of individual channel storeys. Gardiner (1983) reports an average value of 42 for the maximum width-depth ratio for these individual channel storeys. The outcrop extent and borehole data has been used to constrain the lateral geometry of the sandbody. It is likely to be in excess of 8 km (>26,000 ft) in width (Figure 52). Thick channel sandstones occur in other parts of Northumberland at this stratigraphic level (e.g. Cockenheugh Hill [NU 069 342], Sandyburn Ford [NU 1133 2829] and west of Great Wanney Crags near Bellingham [NY 9249 8330]). If these sandstones are correlatable then this sandbody covers an area of 1000-3000 km^2 and has a length in excess of 75 km (Gardiner, 1983).

5.2 SAND-TO-NON-SAND MAPS

As part of this project it was proposed to create a series of net-to-gross sand maps for the onshore succession using the data derived from borehole databasing. The aim of this was to demonstrate the lateral variability onshore as derived from closely spaced boreholes as an aid to understanding the variability offshore. However, the maps cannot truly represent net-to-gross as this tends to be a measure of producible (net) reservoir within an overall gross package, where net sand is defined using a permeability cut-off. The vintage of these boreholes means that only lithological, rather than petrophysical information can be obtained from them and even then this can sometimes be unreliable. Hence rather than referring to them as net-to-gross maps it is better to describe them as sand-to-non-sand maps. Non-sand includes claystone, siltstone, coal, oil-shale, and limestone.

The borehole lithological data was grouped together using the main stratigraphic markers to define sensible packages of strata for mapping purposes. The intervals defined were:

- Wester Coal to Three-Quarter Coal
- Bulman (Main) Coal to Scremerston Main Coal
- Scremerston Main Coal to Caldside Coal
- Caldside Coal to Robie’s Coal
- Robie’s Coal to Dun Limestone
- Dun Limestone to Woodend Limestone
- Woodend Limestone to Doupster Oil-Shale
- Doupster Oil-Shale to Oxford Limestone

The sand-to-non-sand maps for these intervals are shown in Figures 54 and 55. These represent the percentage of sand against non-sand. In most instances it was found that there were not enough data points to properly constrain these maps. Where there were enough data points to construct a sensible map it was found that lateral variability appears to be the norm (e.g. Figure 54C and D, Figure 55C). Whilst it is believed that the majority of this variability is real, other factors that could influence the production of these maps are poor core recovery and poor core description. This lateral variability can also be seen in the borehole correlation panels

(Figures 43-45) and appears to be a reflection of abrupt thickness changes associated with the sandbodies within the succession.

6 Implications for offshore studies

Without a more detailed study of the offshore Scremerston Formation successions it is difficult to be fully confident that the onshore successions are applicable as analogues to those offshore. However, most of the facies described from onshore can be recognised offshore in Well 42/13-2. The exceptions to this are the marine limestone facies and some of the lacustrine facies. In addition some of the channel facies recognised onshore are of similar thickness, grain size and character to the main reservoir sandbody present in Well 42/13-2.

The work described in this report suggests that the main sandbodies in the Berwick area are major stacked channel systems. Typically the thickest channels represent the product of channel belts, i.e. more than one channel superimposed vertically and/or laterally. These fluvial deposits are produced by the lateral switching and migration of individual river channels that produce sandy deposits that are wider and thicker than the original channel dimensions. Gradual migration and shifting of channels results in channel belts that are likely to show a good degree of lateral interconnectivity. Alternatively, channels that show fairly sudden switching of their position due to avulsion events are likely to have more variable or even reduced lateral connectivity. Palaeocurrents at outcrop vary from south-west to south-east, with an overall mean towards the south. It is unknown whether the major stacked channel represent incised valley fills or aggradational sandbodies. The maximum recorded incision of 30 ft (9 m) by the channel above the Dun Limestone, its sheet–like geometry (widths in excess of 8 km (>26,000 ft)) and its restriction to the cycle between the Dun and the Woodend limestones suggests that at least the larger sandbodies are more likely to represent aggradational complexes.

If the offshore channel systems are of similar dimensions then individual channel belts are likely to be fairly thick (~tens to hundreds of feet) and wide (~thousands of feet) but, on a field scale, net-to-gross could vary quite significantly in adjacent wells, linked to their positions with respect to the channel belts. Channels are likely to be braided and hence produce channel belts that are of low sinuosity and are linear to curvilinear in form. Sandbodies are likely to comprise a combination of ribbons and sheets, with sheets more prevalent (width/thickness >15). Various cross-plots exist in the geological literature to try to describe the relationship between width and thickness of fluvial sandbodies (see Figures 56 and 57). Whilst these are useful for estimating channel body width in the subsurface where well constraints are limited, it can be seen from Figure 56 that large numbers of data points produces a wide range of possible widths for any one thickness.

Palaeocurrent analysis from offshore wells give largely southerly-directed palaeocurrent trends (Maynard and Dunay, 1999). Hence reservoir sandbodies are likely to be linear or curvi-linear with a roughly north-south orientation. Maynard & Dunay (1999) suggest that the late Dinantian sandstones were derived from the north and their deposition was probably influenced by fault-controlled lows through the Mid North Sea High. Structural control has also been recognised onshore along the Stublick-Ninety Fathom Fault zone (Leeder et al., 1989) and hence needs to be considered whilst considering reservoir distribution and geometry.

The presence of a number of beds of marine mudstone in Well 42/13-2 indicates periods of repeated marine flooding across the delta plain. These are likely to be fairly extensive and may act as intraformational baffles that would result in the vertical compartmentalisation of potential reservoirs with respect to other sandbodies in the succession. Lateral compartmentalisation occurs when individual channel bodies fail to intersect with adjacent ones. As most of the thicker sandbodies are likely to be the product of channel belts this might also be an issue.

References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

CAMERON, T.D.J. 1993. 5. Carboniferous and Devonian of the Southern North Sea. In: KNOX, R.W.O'B. and CORDEY, W.G. (eds) *Lithostratigraphic nomenclature of the UK North Sea*. British Geological Survey, Nottingham, 93pp.

CLIFF, R.A., DREWERY, S.A. and LEEDER, M.R. 1991. Sourcelands for the Carboniferous Pennine river system: constraints from sedimentary evidence and U/Pb geochronology using zircon and monazite. In: MORTON, A.C., TODD, S.P. and HAUGHTON, P.D.W. (eds) *Developments in sedimentary provenance studies*. Special Publication 57, Geological Society, London, 137-159.

COLLINSON, J.D. 2005. Dinantian and Namurian depositional systems in the southern North Sea. In: COLLINSON, J.D., EVANS, D.J., HOLLIDAY, D.W. and JONES, N.S. (eds) 2005. *Carboniferous Hydrocarbon Geology The Southern North Sea and Surrounding Onshore Areas*. Yorkshire Geological Society Occasional Publication 7, 35-56.

FIELDING, C.R. 1986. Fluvial channel and overbank deposits from the Westphalian of the Durham Coalfield, N.E. England. *Sedimentology*, **33**, 119-140.

FRIEND, P.F., SLATER, M.J. & WILLIAMS, R.C. 1979. Vertical and lateral building or river sandstone bodies, Ebro basin, Spain. *Journal of the Geological Society, London*, **136**, 39-46.

FROST, D.V. 1969. The Lower Limestone Group (Viséan) of the Otterburn district, Northumberland. *Proceedings of the Yorkshire Geological Society*, **37**, 277-309.

GARDINER, A.R. 1983. Sedimentological studies of the Scremerston Coal and Lower Limestone groups in the Northumberland Basin. Unpublished PhD thesis, Univeristy of Leeds.

GARDINER, A.R. 1984. A braided river sheet sandstone in the Lower Limestone Group of the Northumberland Basin. European Dinantian Environments, Abstracts from the 1st Meeting, Manchester April 11-13 1984. Department of Earth Sciences, Open University, 105-107.

GARDINER, A.R. 1997. Sedimentological analysis of cores 1 to 3 (7383'-7506') from Mobil North Sea Well 42/13-2. Robertson Research International Limited Report No. 8009/Id.

GIBLING, M.R. 2006. Width and thickness of fluvial channel bodies and valley fills in the geological record: a literature compilation and classification. *Journal of Sedimentary Research*, **76**, 731-770.

GUION, P.D., FULTON, I.M. and JONES, N.S. 1995. Sedimentary facies of the coal-bearing Westphalian A and B north of the Wales-Brabant High. In: WHATELEY, M.K.G. and SPEARS, D.A. (eds) *European Coal Geology*. Geological Society Special Publication No. **82**, 45-78.

HAMPSON, G.J., ELLIOTT, T. & DAVIES, S. 1997. The application of sequence stratigraphy to Upper Carboniferous fluvio-deltaic strata of the onshore UK and Ireland: Implications for the southern North Sea. *Journal Of the Geological Society*, **154**, 719-733

JONES, N.S. and GLOVER, B.W. 2005. Fluvial sandbody architecture, cyclicity and sequence stratigraphical setting; implications for hydrocarbon reservoirs: the Westphalian C and D of the Osnabrück-Ibbenbüren area, northwest Germany. In COLLINSON, J.D., EVANS, D.J., HOLLIDAY, D.W. and JONES, N.S. (eds) *Carboniferous hydrocarbon geology: the southern North Sea and surrounding onshore areas*. Yorkshire Geological Society Occasional Publication 7, 57-74.

LEEDER, M.R. 1975. Lower Border Group (Tournaisian) stromatolites from the Northumberland Basin. *Scottish Journal of Geology*, **11**, 207-226.

LEEDER, M.R., FAIRHEAD, D., LEE, A., STUART, G., CLEMMEY, H., EL-HADDAHEH, B. and GREEN, C. 1989. Sedimentary and tectonic evolution of the Northumberland Basin. In: ARTHURTON, R.S., GUTTERIDGE, P. and NOLAN, S.C. (eds) *The Role of Tectonics in Devonian and Carboniferous Sedimentation in the British Isles*. Occasional Publication of the Yorkshire Geological Society, 6, 207-223.

MARION, G.M., SCHLESINGER, W.H. and FONTEYN, P.J. 1985. Caldep: a regional model for soil $CaCO_3$ (caliche) deposition in southwestern deserts. *Soil Science*, **139,** 468-481.

MAYNARD, J.R. and DUNAY, R.E. 1999. Reservoirs of the Dinantian (Lower Carboniferous) play of the southern North Sea. In: FLEET, A.J. and BOLDY, S.A.R. (eds) Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference, 729-745.

MJØS, R. WALDERHAUG, O. and PRESTHOLM, E. 1993. Crevasse splay geometries in the Middle Jurassic Ravenscar Group of Yorkshire. In: MARZO, M. and PUIDEFABREGAS, C. (eds) *Alluvial Sedimentation*. Special Publication of the International Association of Sedimentologists, 17, 167-184.

PARNELL, J. 1988. Lacustrine petroleum source rock in the Dinantian Oil Shale Group, Scotland: a review. In: FLEET, A.J., KELTS, K. and TALBOT, M.R. (eds) *Lacustrine Petroleum Source Rock*. Geological Society Special Publication No.40, 235-246.

RILEY, N.J. 1997a. Interpretation of the depositional environments derived from direct observation of selected core chips from Mobil 42/13-2. British Geological Survey Technical Report WH97/153C.

RILEY, N.J. 1997b. Recognition of marine flooding surfaces in Mobil 42/13-2. British Geological Survey Technical Report WH97/159C.

SCHILLER, H.J. 1980. X-Ray textural analysis of clays and compacted shales. In: *Abstracts of the International Association of Sedimentologists 1st European Meeting, Bochum 1980*, pp 17-20.

THOMAS, R.G., SMITH, D.G., WOOD, J.M., VISSER, J., CALVERLEY-RANGE, E.A. and KOSTER, E.H. 1987. Inclined heterolithic stratification - terminology, description, interpretation and significance. *Sedimentary Geology*, **53**, 123-179.

TURNER, B.R. & MONRO, M. 1987. Channel formation and migration by mass-flow processes in the Lower Carboniferous fluviatile Fell Sandstone Group, northeast England. *Sedimentology*, **34**, 1107-1122.

WRIGHT, V.P. and TUCKER, M.E. 1991. Calcretes: An Introduction. In: WRIGHT, V.P. and TUCKER, M.E. (eds) *Calcretes. Reprint Series Volume 2 of the International Association of Sedimentologists*. Blackwells, Oxford, 1-22.

WRIGHT, V.P. & VANSTONE, S.D. 2001. Onset of Late Palaeozoic glacio-eustasy and the evolving climates of low latitude areas: a synthesis of current understanding. *Journal of the Geological Society*, **158**, 579-582.

Figure 1. Location map of the area around Berwick-upon-Tweed to show the simplified geology and the main localities studied. Geology derived from BGS Digmap50 digital data.

Figure 2. Generalised stratigraphy of the Scremerston Formation at outcrop and comparisons with the offshore nomenclature.

Figure 3. Sedimentological log of cores 1, 2 and 3 from Well 42/13-2. Key to graphic log symbols are given in Figure 8.

Figure 4. Cross-plot of horizontal permeability against porosity for all data from cores 1-3, Well 42/13-2.

Figure 5. Cross-plot of horizontal permeability against porosity for the channel facies, data points grouped by grain size (Cores 1-3, Well 42/13-2).

Figure 6. Proposed correlation between the onshore and offshore Scremerston Formation succession.

Figure 7. Proposed correlation of Well 42/13-2 with nearby wells.

Figure 8. Sedimentological log of part of the coastal outcrop section south of Spittal. Redrawn, with modifications, from Gardiner (1983).

Figure 9. Terminology for describing the cross-sectional geometry of channel bodies. Redrawn with minor modifications from Gibling (2006). Ribbon and sheet definitions from Friend et al. (1979).

Figure 10. Major stacked channel facies above the Dun Limestone (DL). Three channel storeys, labelled 1-3, are separated by floodplain mudstones (red arrows). Marshall Meadows Bay, north of Berwick-upon-Tweed [NT 98169 57040].

Figure 11. Cross-bedded channel sands of the Major Stacked Channel facies. Face is 85ft (26m) in height, comprising a number of channel storeys. St John's Haven, north of Berwick [NT 99053 55702].

Figure 12. Line drawing of the Major Stacked Channel facies above the Dun Limestone to show the hierarchy of bounding surfaces that can be recognised. Marshall Meadows Bay, north of Berwick-upon-Tweed.

Figure 13. Example of the Major Stacked Channel facies to show the laterally extensive basal erosion surfaces (arrowed) that can be used to differentiate individual channel storeys. The upper channel is separated from the middle channel by a discontinuous mudstone bed. Face is approximately 90ft in height. St John's Haven [NT 98709 56304].

Figure 14. Example of the Major Stacked Channel facies. Channel bases are arrowed. Tenquarter Freestone, A1167 Road, Springhill Reservoir [NU 00082 50654].

Figure 15. Planar-tabular set of cross-bedding in the Major Stacked Channel facies. Rucksack for scale is 0.5m in height. Succession above Dun Limestone, St John's Haven [NT 99203 55555].

Figure 16. Trough cross-bedding in the Major Stacked Channel facies. Rucksack for scale is 0.5m in height. Succession above Dun Limestone, Tods Loup [NT 97563 57874].

Figure 17. Coset of cross-bedding from the Major Stacked Channel facies. Succession above the Dun Limestone, Huds Head [NU 01412 50545].

Figure 18. Example of a major single storey channel. Note the undulatory erosive base. Face is about 26 ft (8 m) high. Skipper Sandstone, The Skipper [NU 01535 50345].

Figure 19. Minor sandy channel facies in the interval below the Dun Limestone (DL). Large mudstone intraclasts at the base of the channel are arrowed. The upper part shows fining-upwards. Spittal foreshore [NU 01111 50923].

Figure 20. Cross-bedding foresets with silty drapes (arrowed). Minor sandy channel facies in the interval below the Dun Limestone. Spittal foreshore [NU 01111 50923].

Figure 21. Photomontage to show the relationship between two minor heterolithic channels and adjacent floodplain facies. Succession below the Dun Limestone at Huds Head, Spittal [NU 01258 50727].

Figure 22. Lateral accretion bedding (inclined heterolithic stratification) within a minor heterolithic channel. The bedding can be clearly seen to dip towards the left (arrowed) and represents the deposits of a point bar within a meandering channel. Succession below the Dun Limestone, Huds Head, Spittal foreshore [NU 01235 50793].

Figure 23. Lateral accretion bedding (inclined heterolithic stratification) within a minor heterolithic channel. Successive heterolithic bedsets dip towards the right (arrowed in black). The channel base is marked by the red arrow. Succession below the Dun Limestone, Huds Head, Spittal foreshore [NU 01223 50791].

Figure 24. Trough-shaped scour (arrowed) in a minor heterolithic crevasse channel. Succession below the Dun Limestone, Huds Head, Spittal foreshore [NU 01216 50779].

Figure 25. Upwards-coarsening interdistributary bay delta above the Woodend Limestone. The Skipper, south of Berwick [NU 01487 50452].

Figure 26. Climbing wave ripple form sets (arrowed) in prodelta silts. Succession above the Woodend Limestone, The Skipper [NU 01465 50523].

Figure 27. *Rhizocorallium* burrows in prodelta silts above Woodend Limestone. The Skipper [NU 01465 50520].

Figure 28. Wave ripple cross-lamination in the upper part of an interdistributary bay facies. Succession above the Woodend Limestone, The Skipper [NU 01487 50452].

Figure 29. Photograph of the succession immediately above and below the Dun Limestone at the north-east end of Marshall Meadows Bay [NT 98180 57070]. Below the Dun Limestone, an upwards-coarsening interdistributary bay facies is erosively truncated by a major single storey channel. This fines upwards into muddy abandonment facies. Above the Dun Limestone a stacked major channel system is present.

Figure 30. Strandplain/barrier-island facies in the succession immediately above the Doupster Oil-Shale. Two upwards-coarsening sandy lobes (marked SP) are separated by a bed of lagoonal muds. Red Shin, [NU 01629 50268].

Figure 31. Marine limestone facies, Dun Limestone (DL), overlying the Dun Coal (arrowed). As the outcrop is traced laterally up the cliff face the Dun Coal is progressively eroded by the overlying limestone. Marine mudstone can be seen overlying the Dun Limestone (top left). Huds Head, Spittal [NU 01269 50729].

Figure 32. Marine limestone facies, comprising argillaceous limestone with common Siphonodendron junceum (SJ) and Siphonodendron martini (SM) corals. Woodend Limestone, The Skipper, Spittal [NU 01455 50499].

Figure 33. Marine mudstone facies, comprising laminated dark grey mudstones with siderite nodules. Succession immediately above the Dun Limestone at Huds Head, Spittal [NT 01269 50729].

Figure 34. Muddy, slumped channel bank collapse deposits associated with the Red Shin Sandstone. Red Shin [NU 01699 50246].

Figure 35. Slumped and burrowed sandy siltstone fill to abandoned channel plug. Minor heterolithic channel in succession below the Dun Limestone at Huds Head, Spittal [NU 01223 50785].

Figure 36. Burrowing in the upper part of a major channel sandbody. Tenquarter Freestone, A1167 road section, Springhill Reservoir [NU 00097 50611].

Figure 37. Calcrete palaeosol below the Woodend Limestone. Carbonate nodules form the prominent yellow brown irregular nodules, some of which are arrowed. The Skipper, Spittal [NU 01448 50500].

Figure 38. Grey alluvial palaeosol facies with vertical ironstone (siderite) nodules (arrowed). Huds Head, Spittal [NU01261 50714].

Figure 39. Gley palaeosol facies (GP) overlain by a coaly mudstone. Huds Head, Spittal [NU 01214 50769].

Figure 40. Lacustrine facies, comprising a lacustrine limestone, known as a cementstone. The compass clinometer for scale is 10 x 6 cm. Red Shin, Spittal [NU 01663 50261].

Figure 41. Lacustrine facies, comprising an algal bed (AB) of rounded oncolites and the Doupster Oil-Shale, forming the prominent bed of dark mudstone (arrowed). Red Shin, Spittal [NU 01663 50261].

Figure 42. Map of the Berwick area to show the locations of the boreholes studied.

Figure 43. Borehole correlation through the upper part of the Fell Sandstone to lower part of the Scremerston Formation (Bulman Main Coal level) in the Berwick area of N.E. England.

Figure 44. Borehole correlation through the upper part of the Scremerston Formation (Bulman Main Coal to Dun Limestone) in the Berwick area of N.E. England.

Figure 45. Borehole correlation through the upper part of the Scremerston Formation and lower part of the Yoredale Formation in the Berwick area of N.E. England.

Figure 46. Generalised stratigraphy of the Scremerston Formation to show the sandbodies illustrated in the more detailed palaeogeography maps.

Figure 47. Schematic palaeogeography map to show the Ten-Quarter Freestone channels.

Figure 48. Schematic palaeogeography map to show the Bulman Rock channel.

Figure 49. Schematic palaeogeography map to show the Scremerston Main Rock channels.

Figure 50. Schematic palaeogeography map to show the Robie's Sandstone channel.

Figure 51. Schematic palaeogeography map to show the channel below the Dun Limestone.

Figure 52. Schematic palaeogeography map to show the channel above the Dun Limestone.

Figure 53. Correlation panel to show the facies above and below the Dun Limestone in the area around Marshall Meadows Bay. Reproduced with modifications from Gardiner (1983).

Figure 54. Sand-to-non-sand maps for a number of stratigraphic intervals in the Scremerston and Yoredale formations.

Figure 55. Sand-to-non-sand maps for a number of stratigraphic intervals in the Scremerston Formation.

Figure 56. Log-log cross-plot of thickness versus width for fluvial sandbodies. This is reproduced from Shanley (2004) and represents a dataset of 595 fluvial sandbodies, largely derived from outcrop descriptions from the geological literature.

Figure 57. Cross-plot of Carboniferous sandbody thickness versus sandbody width. Taken from outcrop analogue data (redrawn from ECL 1990).

Table 1. Sedimentary facies recognised from Cores 1 – 3 of Well 42/13-2.

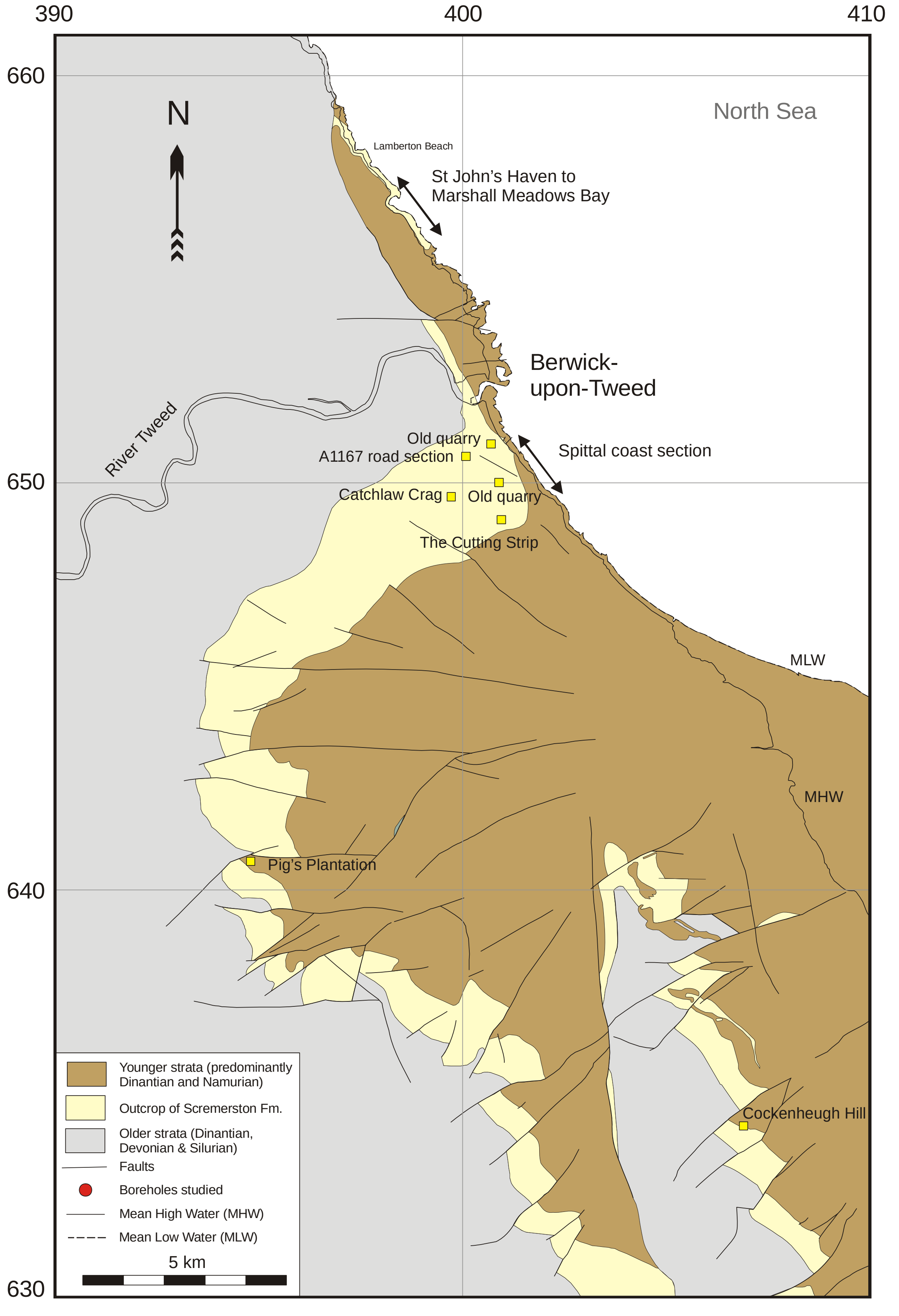


Figure 1. Location map of the area around Berwick-upon-Tweed to show the simplified geology and the main localities studied. Geology derived from BGS Digmap50 digital data.

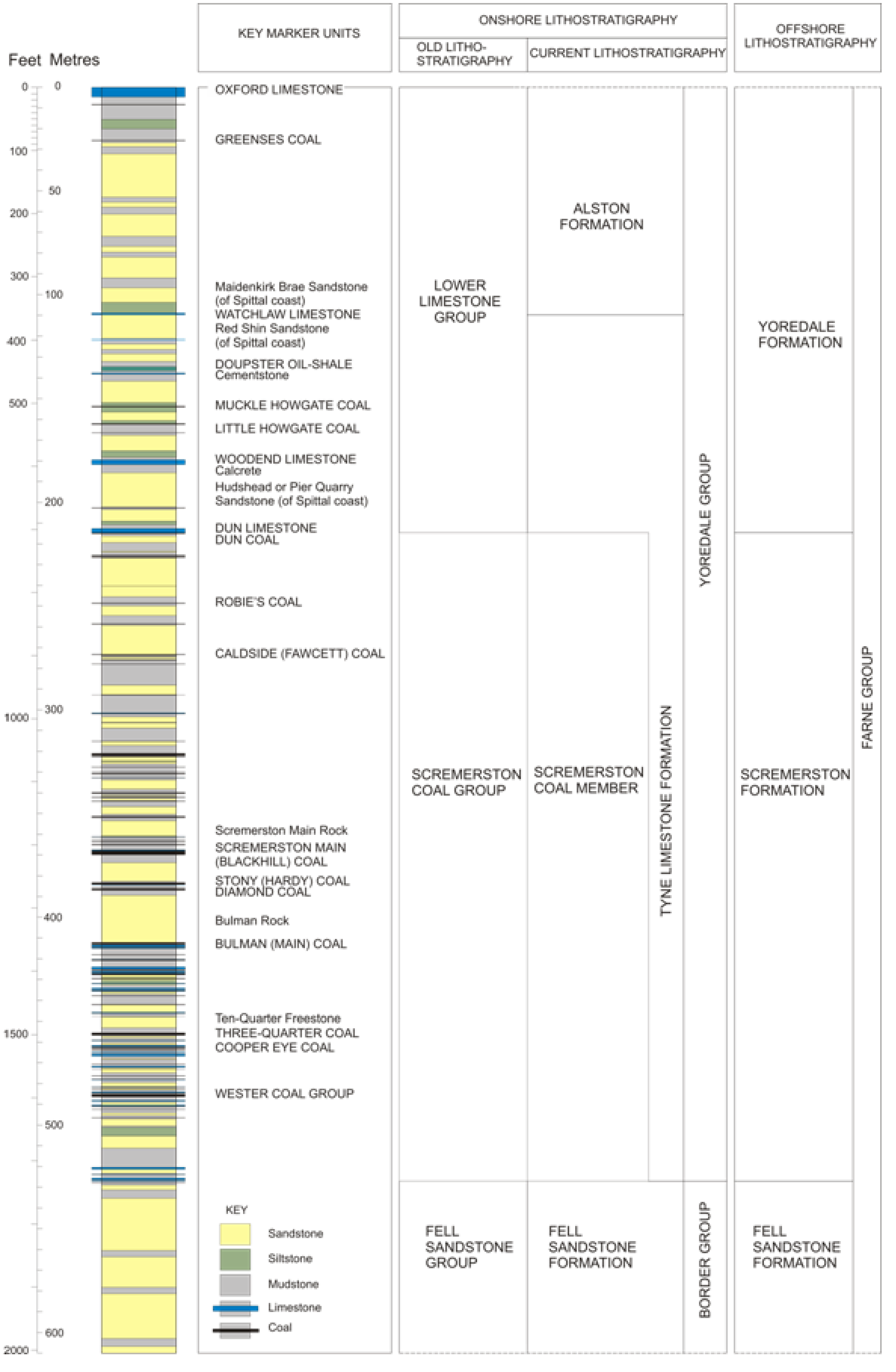


Figure 2. Generalised stratigraphy of the Scremerston Formation at outcrop and comparisons with the offshore nomenclature.

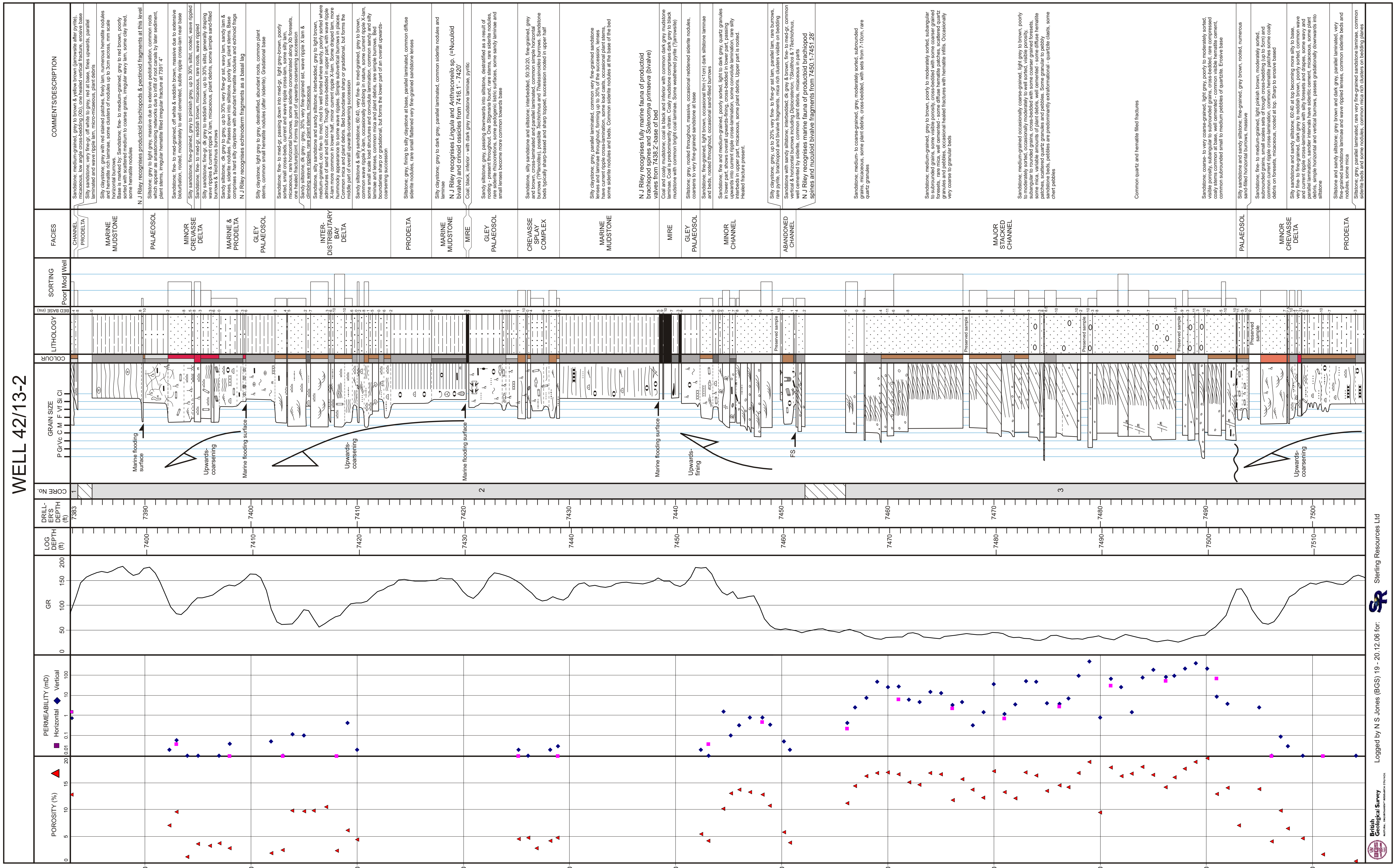


Figure 3. Sedimentological log of cores 1, 2 and 3 from Well 42/13-2. Key to graphic log symbols are given in Figure 8.

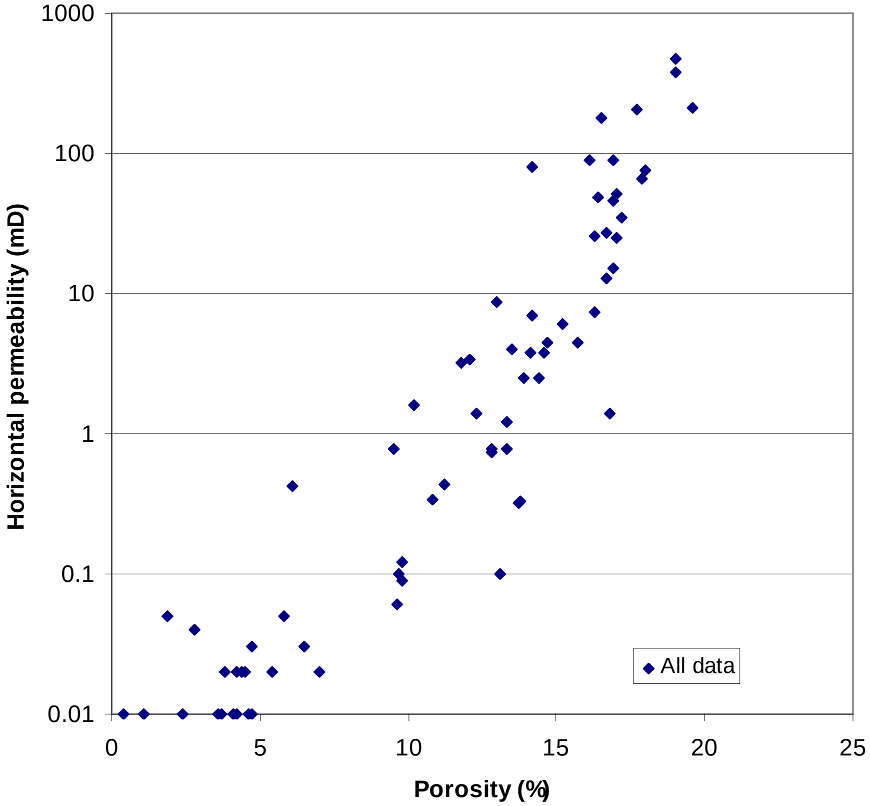


Figure 4. Cross-plot of horizontal permeability against porosity for all data from cores 1-3, Well 42/13-2.

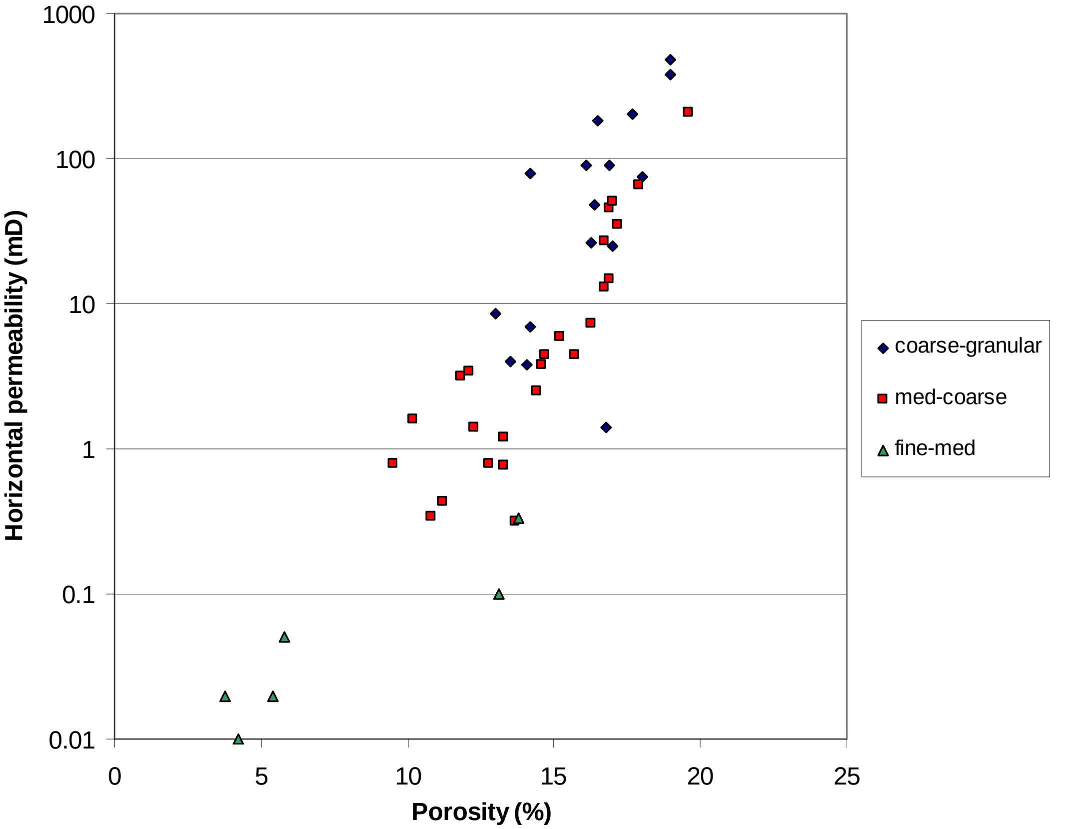


Figure 5. Cross-plot of horizontal permeability against porosity for the channel facies, data points grouped by grain size (Cores 1-3, Well 42/13-2).

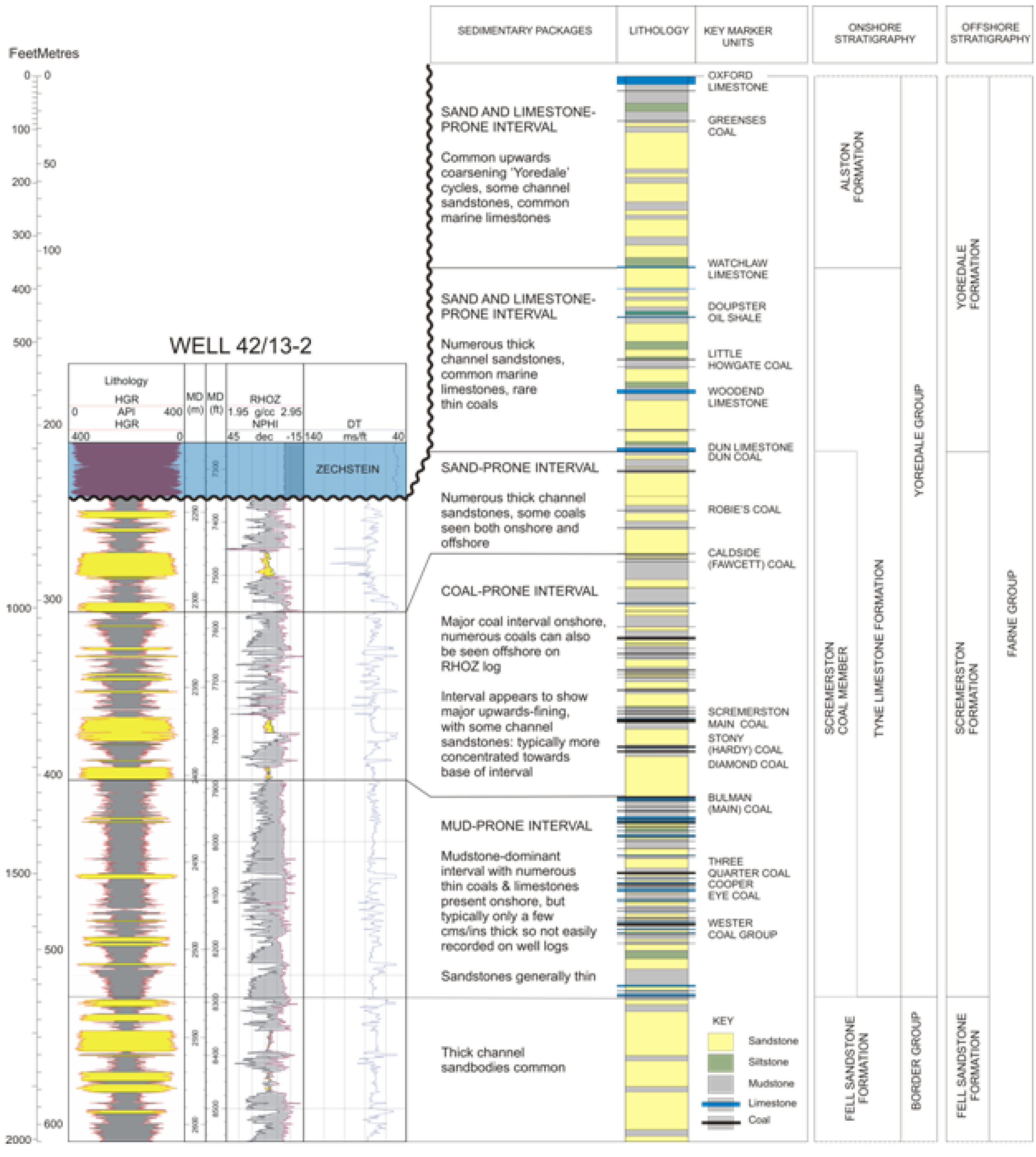


Figure 6. Proposed correlation between the onshore and offshore Scremerston Formation succession.

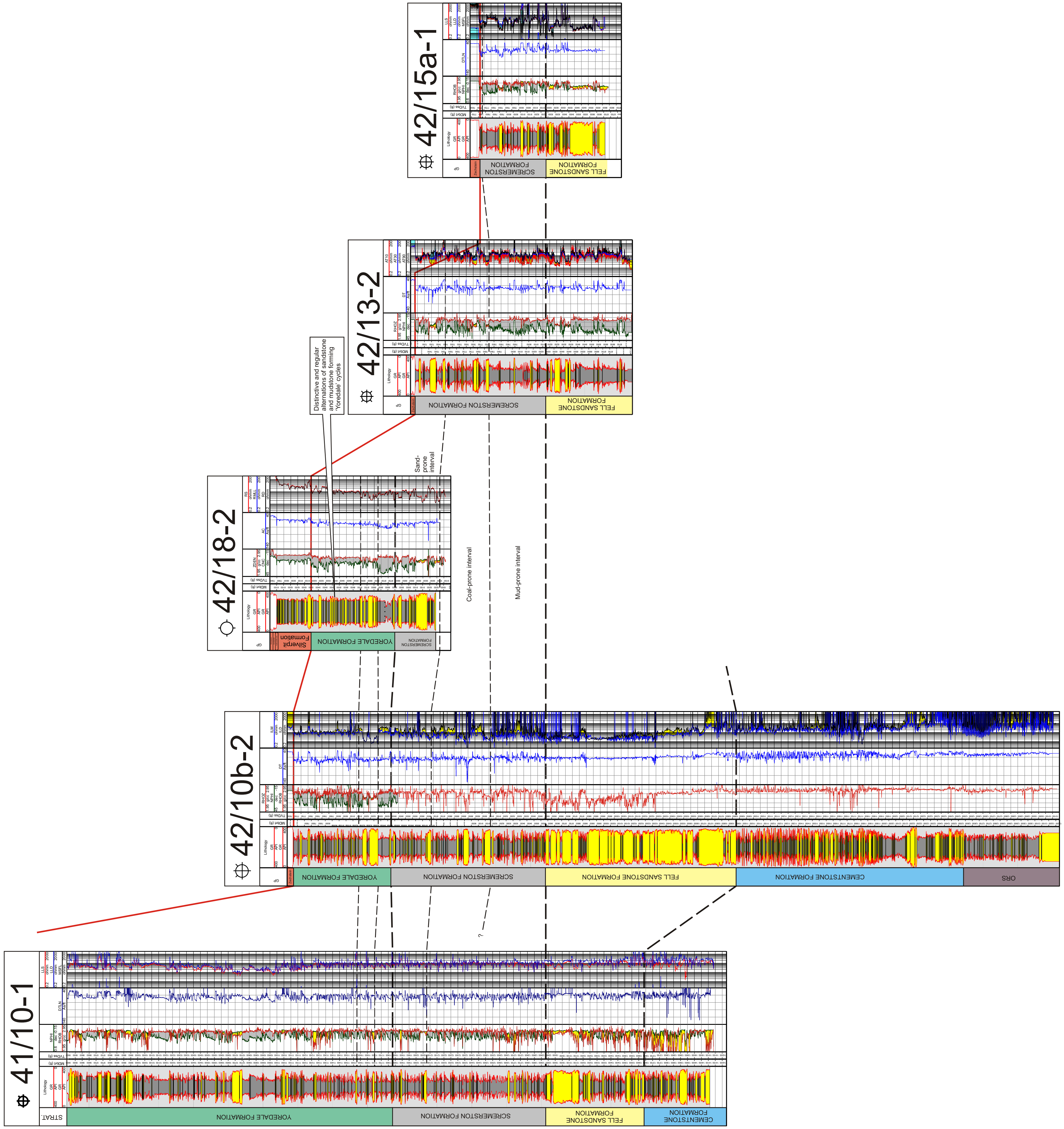


Figure 7. Proposed correlation of Well 42/13-2 with nearby wells.

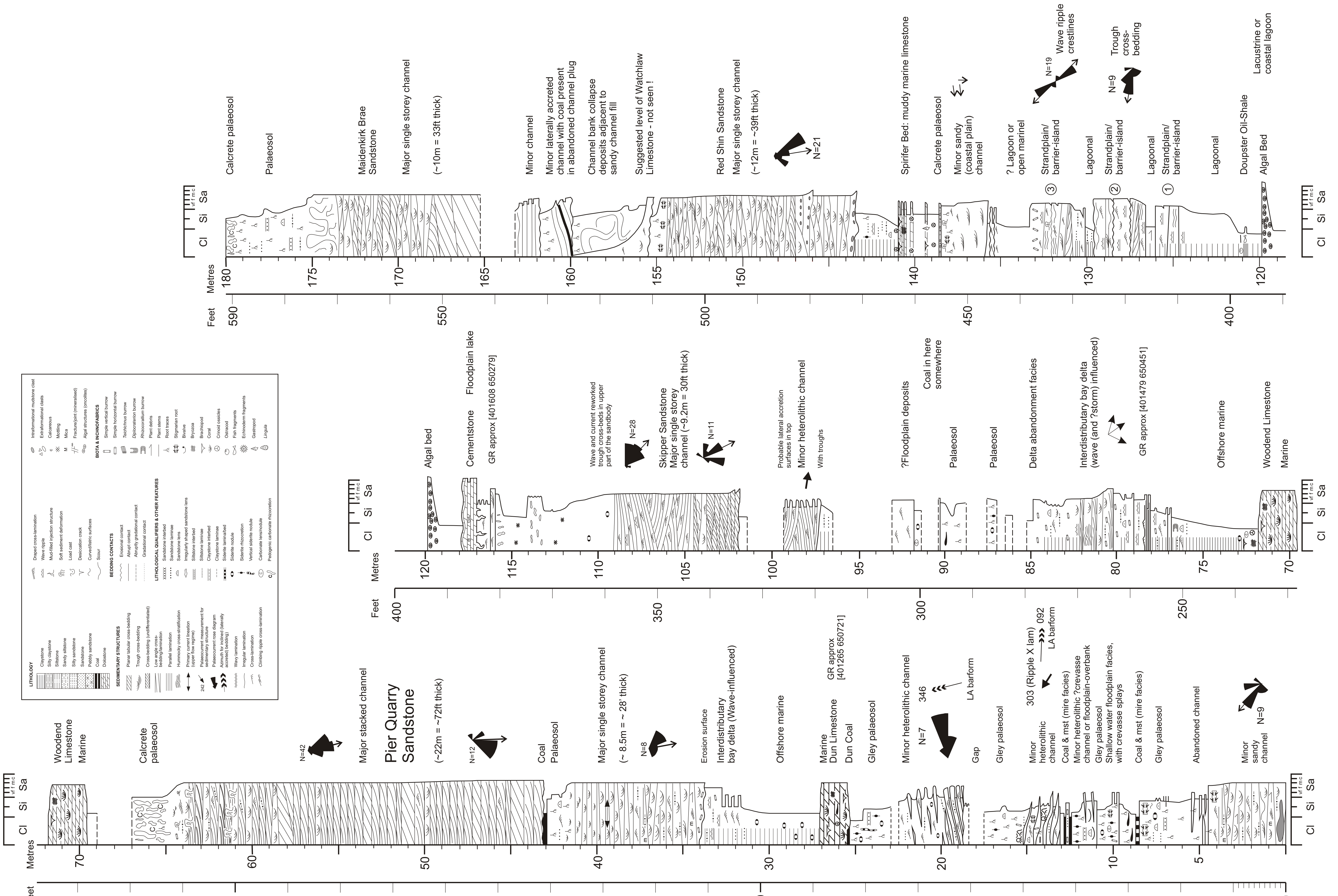


Figure 8. Sedimentological log of part of the coastal outcrop section south of Spital. Redrawn, with modifications, from Gardiner (1983).

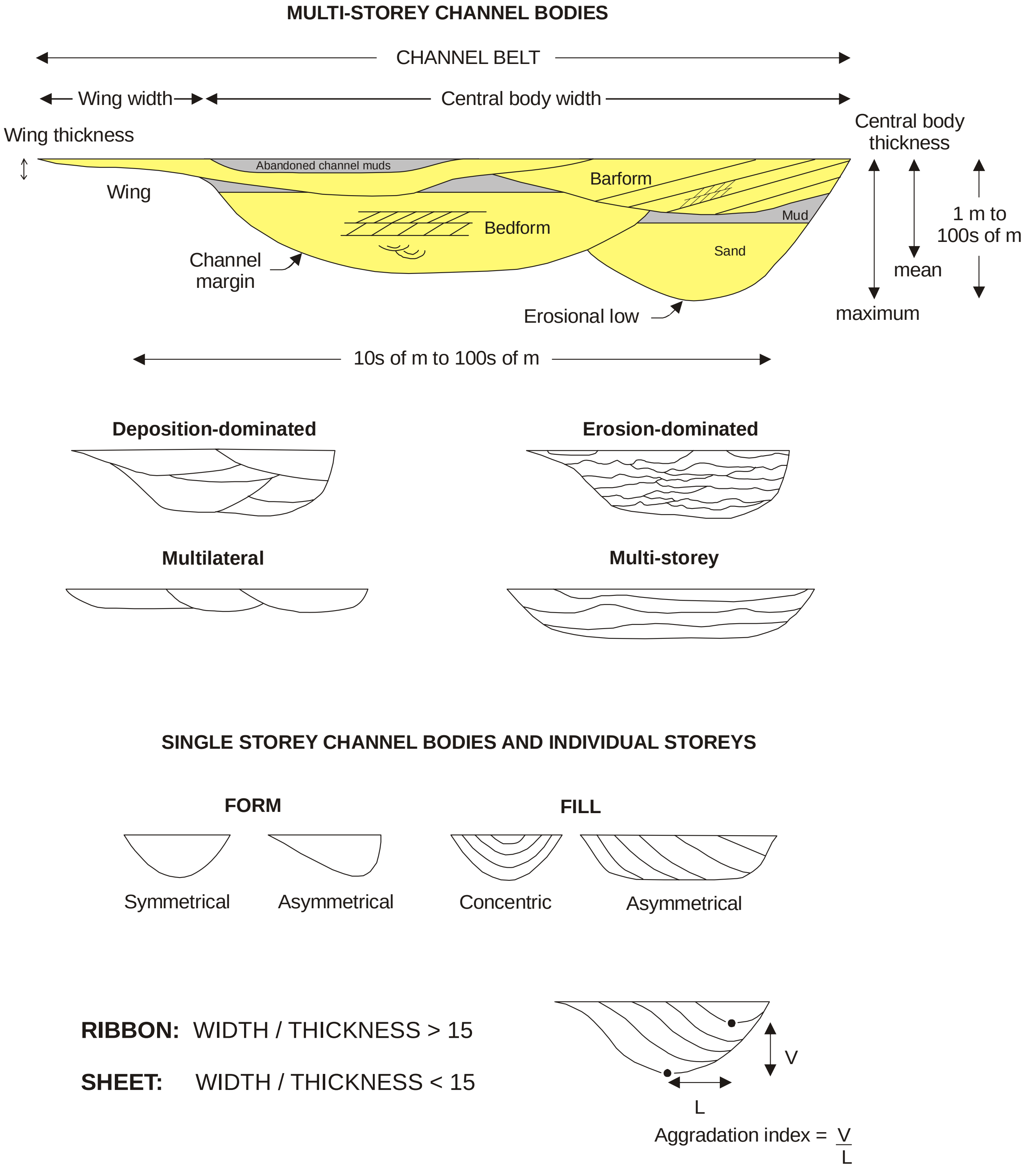
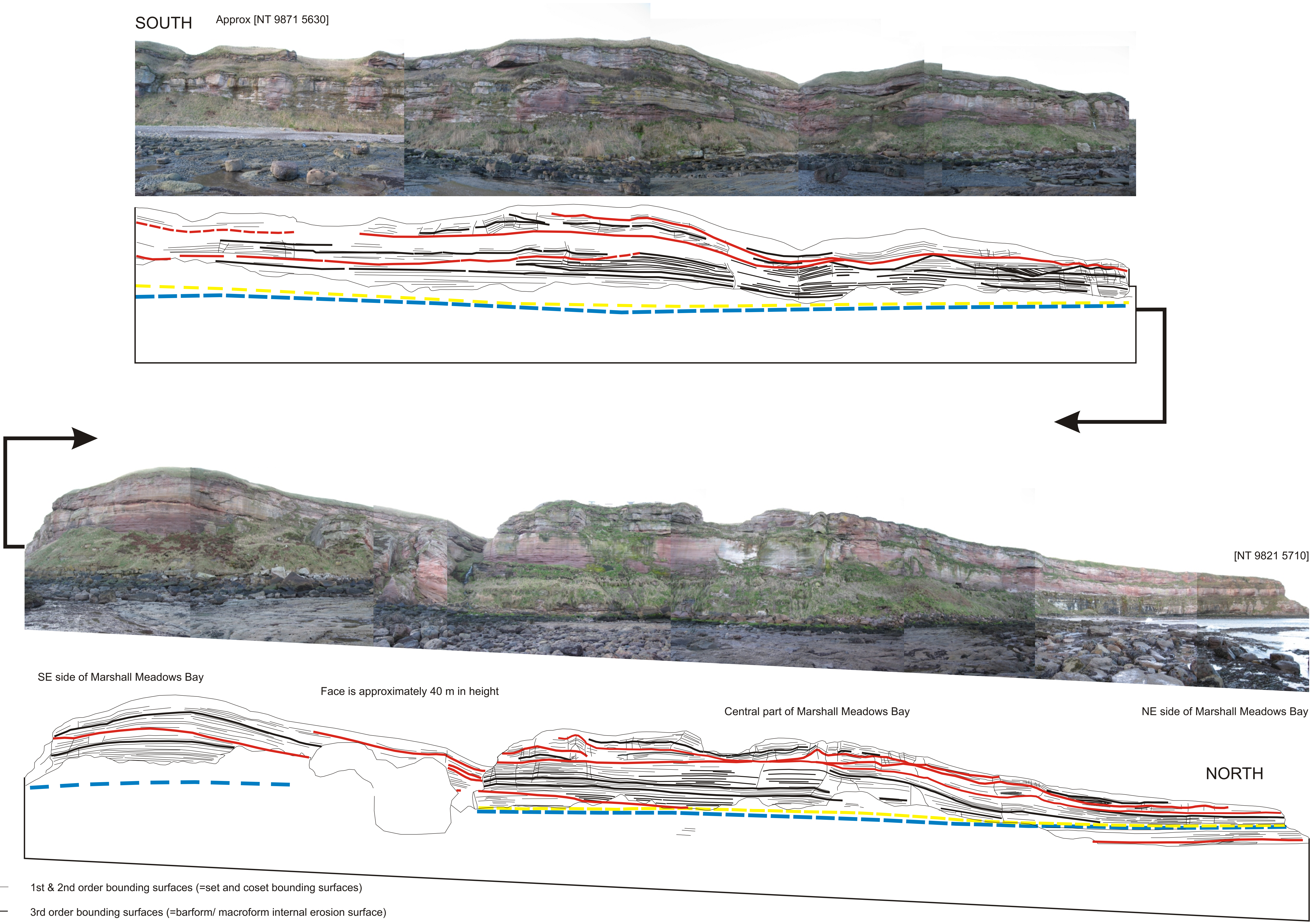


Figure 9. Terminology for describing the cross-sectional geometry of channel bodies. Redrawn with minor modifications from Gibling (2006). Ribbon and sheet definitions from Friend et al. (1979).

Figure 10. Major stacked channel facies above the Dun Limestone (DL). Three channel storeys, labelled 1-3, are separated by floodplain mudstones (red arrows). Marshall Meadows Bay, north of Berwick-upon-Tweed [NT 98169 57040]. Face is approximately 130 Ft (40m) in height.

Figure 11. Cross-bedded channel sands of the Major Stacked Channel facies. Face is approximately 85ft (26m) in height, comprising a number of channel storeys. St John's Haven, north of Berwick [NT 99053 55702].



1st & 2nd order bounding surfaces (=set and coset bounding surfaces)

3rd order bounding surfaces (=barform/ macroform internal erosion surface)

4th order bounding surface (=upper/lower bounding surface of a barform/ macroform)

5th order bounding surface (=channel base)

6th order bounding surface (=base of channel belt)

Level of Dun Limestone

Dashed lines represent areas of uncertainty of the position of the bounding surface due to poor exposure

Figure 12. Line drawing of the Major Stacked Channel facies above the Dun Limestone to show the hierarchy of bounding surfacse that can be recognised. Marshall Meadows Bay, north of Berwick-uponTweed.

Figure 13. Example of the Major Stacked Channel facies to show the laterally extensive basal erosion surfaces (arrowed) that can be used to differentiate individual channel storeys. The upper channel is separated from the middle channel by a discontinuous mudstone bed. Face is approximately 90ft in height. St John’s Haven [NT 98709 56304].

Figure 14. Example of the Major Stacked Channel facies. Channel bases are arrowed. Tenquarter Freestone, A1167 Road, Springhill Reservoir [NU 00082 50654].

Figure 15. Planar-tabular set of cross-bedding in the Major Stacked Channel facies. Rucksack for scale is 0.5m in height. Succession above Dun Limestone, St John’s Haven [NT 99203 55555].

Figure 16. Trough cross-bedding in the Major Stacked Channel facies. Rucksack for scale is 0.5m in height. Succession above Dun Limestone, Tods Loup [NT 97563 57874].

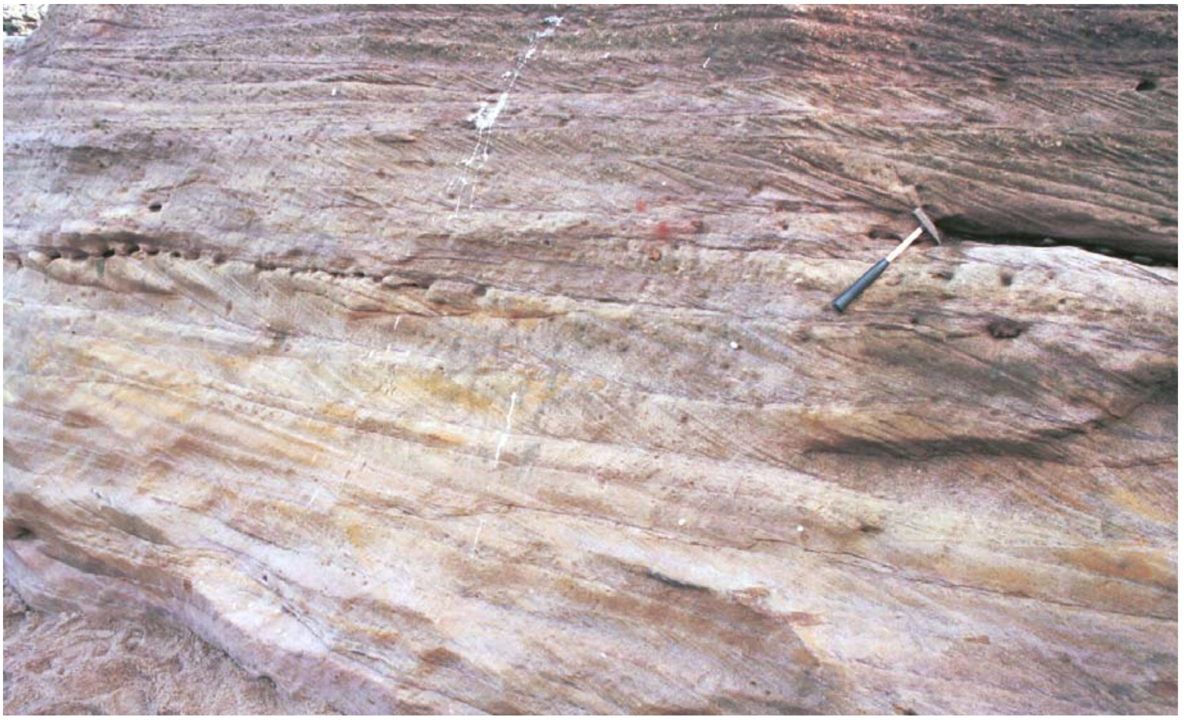


Figure 17. Coset of cross-bedding from the Major Stacked Channel facies. Pier Quarry Sandstone in the succession above the Dun Limestone, Huds Head [NU 01412 50545].

Figure 18. Example of a major single storey channel. Note the undulatory erosive base. Face is about 26 ft (8 m) high. Skipper Sandstone, The Skipper [NU 01535 50345].

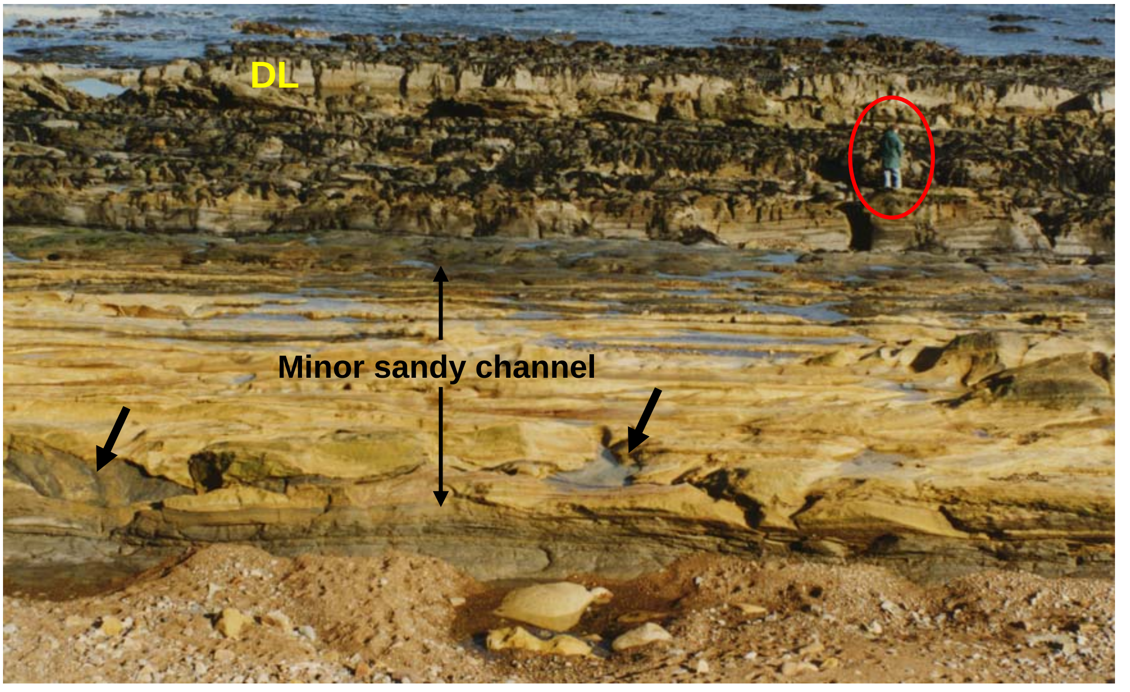


Figure 19. Minor sandy channel facies in the interval below the Dun Limestone (DL). Large mudstone intraclasts at the base of the channel are arrowed. The upper part shows fining-upwards. Spittal foreshore [NU 01111 50923].

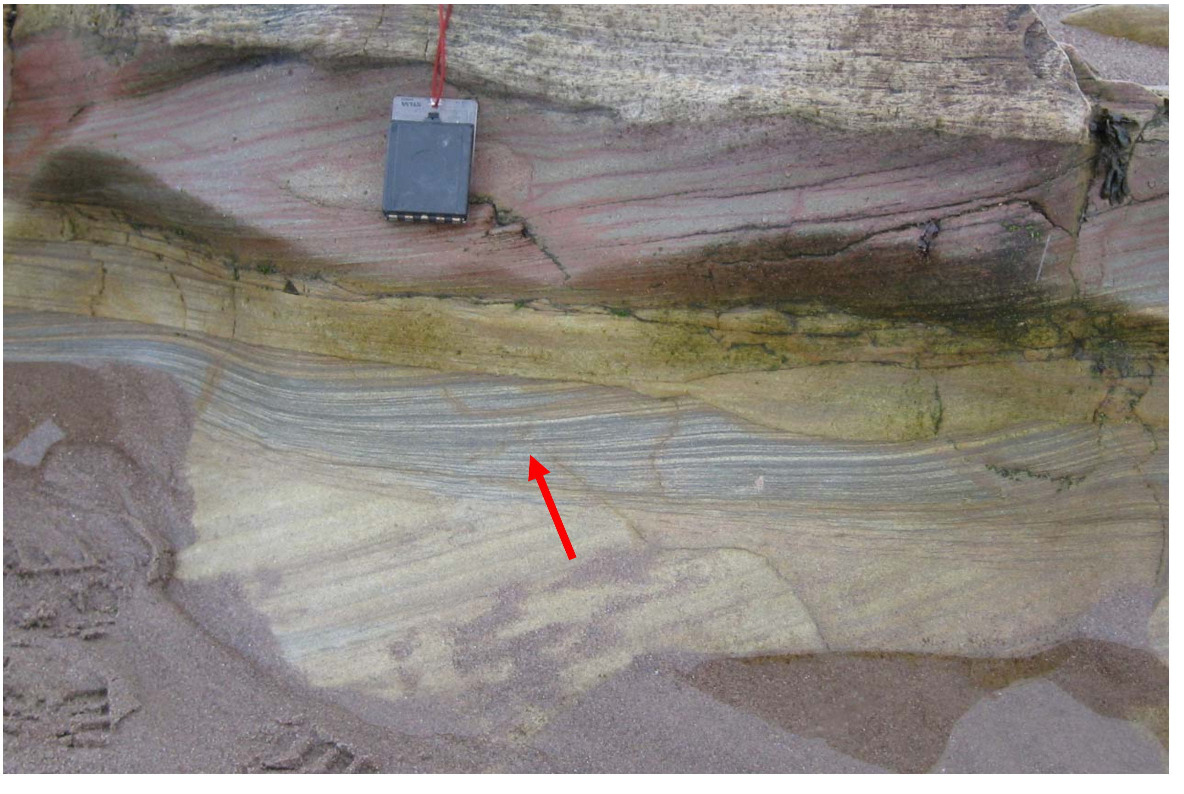


Figure 20. Cross-bedding foresets with silty drapes (arrowed). Minor sandy channel facies in the interval below the Dun Limestone. Spittal foreshore [NU 01111 50923].

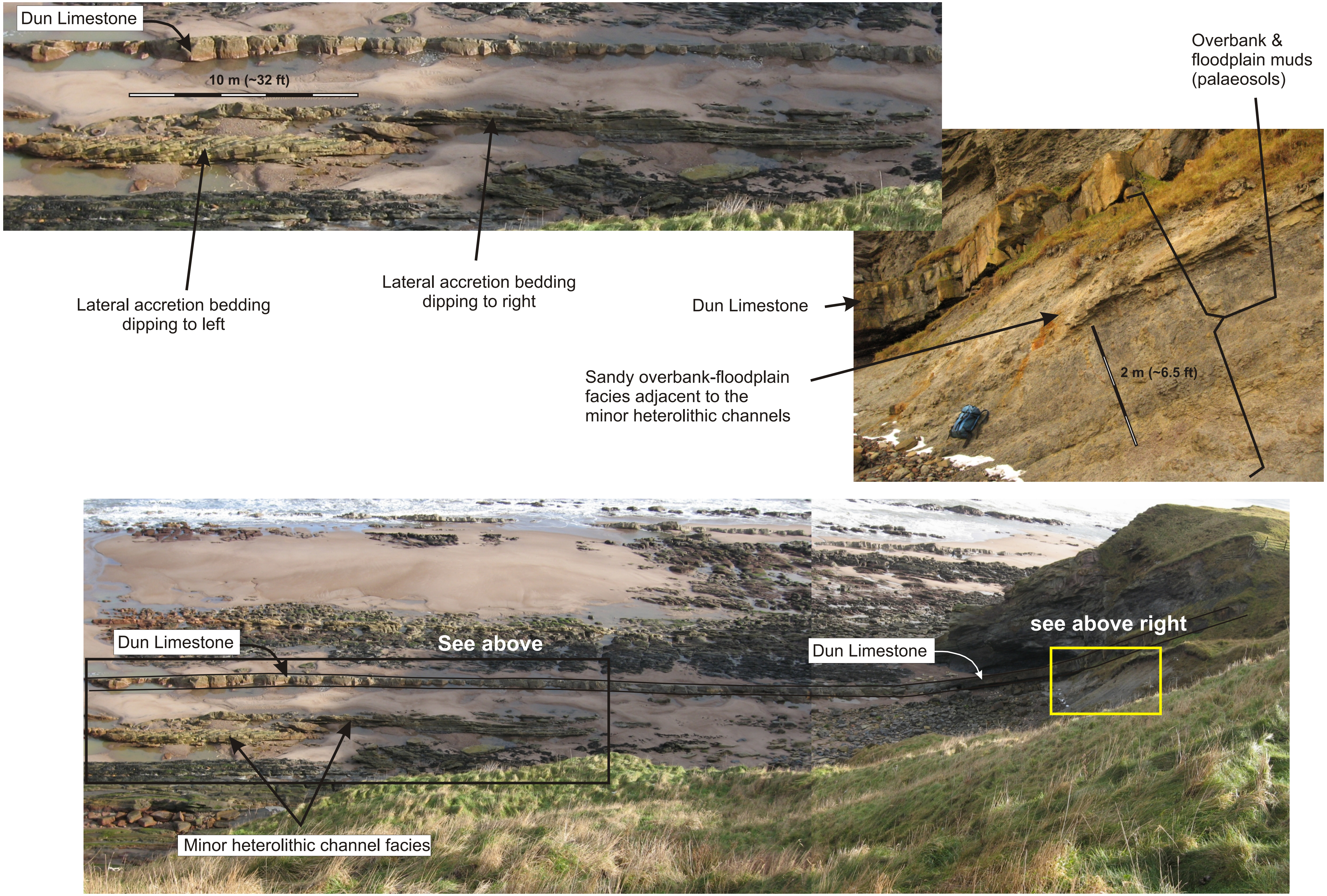


Figure 21. Photomontage to show the relationship between two minor heterolithic channels and adjacent floodplain facies. Huds Head, Spittal [NU 01258 50727].

Figure 22. Lateral accretion bedding (inclined heterolithic stratification) within a minor heterolithic channel. The bedding can be clearly seen to dip towards the left (arrowed) and represents the deposits of a point bar within a meandering channel. Succession below the Dun Limestone, Huds Head, Spittal foreshore [NU 01235 50793].

Figure 23. Lateral accretion bedding (inclined heterolithic stratification) within a minor heterolithic channel. Successive heterolithic bedsets dip towards the right (arrowed in black). The channel base is marked by the red arrow. Succession below the Dun Limestone, Huds Head, Spittal foreshore [NU 01223 50791].

Figure 24. Trough-shaped scour (arrowed) in a minor heterolithic crevasse channel. Succession below the Dun Limestone, Huds Head, Spittal foreshore [NU 01216 50779].

Figure 25. Upwards-coarsening interdistributary bay delta above the Woodend Limestone. The Skipper, south of Berwick [NU 01487 50452].

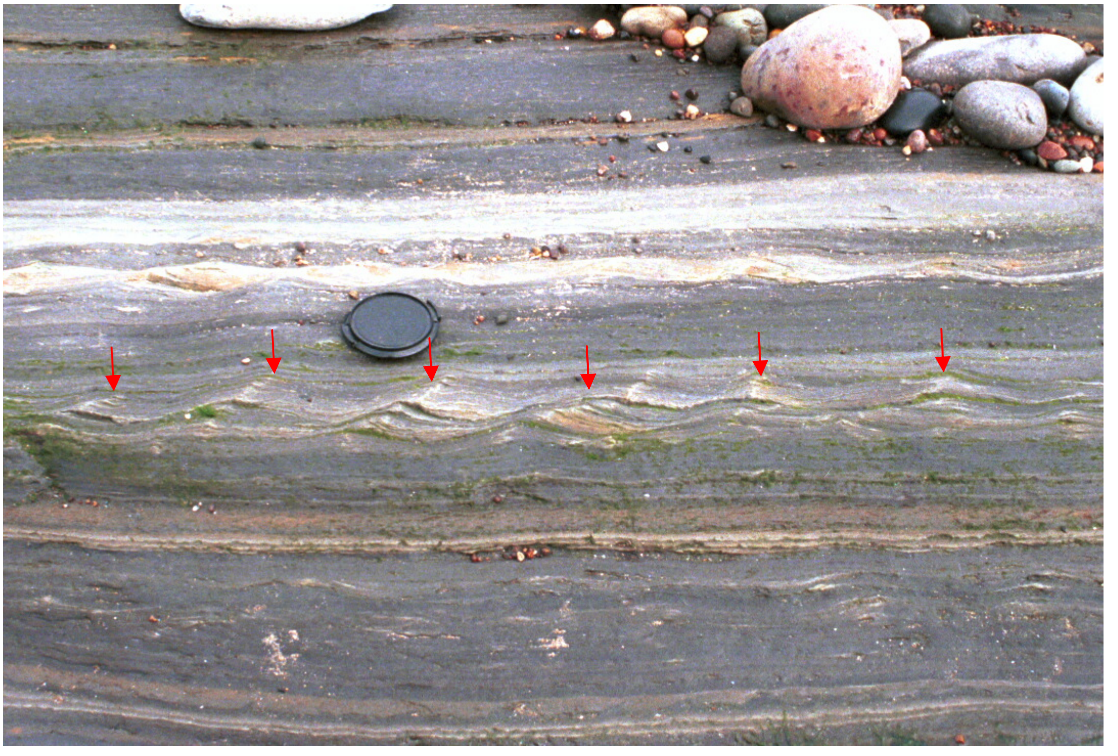


Figure 26. Climbing wave ripple form sets (arrowed) in prodelta silts. Succession above the Woodend Limestone, The Skipper [NU 01465 50523].

Figure 27. *Rhizocorallium* burrows in prodelta silts above Woodend Limestone. The Skipper [NU 01465 50520].

Figure 28. Wave ripple cross-lamination in the upper part of an interdistributary bay facies. Succession above the Woodend Limestone, The Skipper [NU 01487 50452].

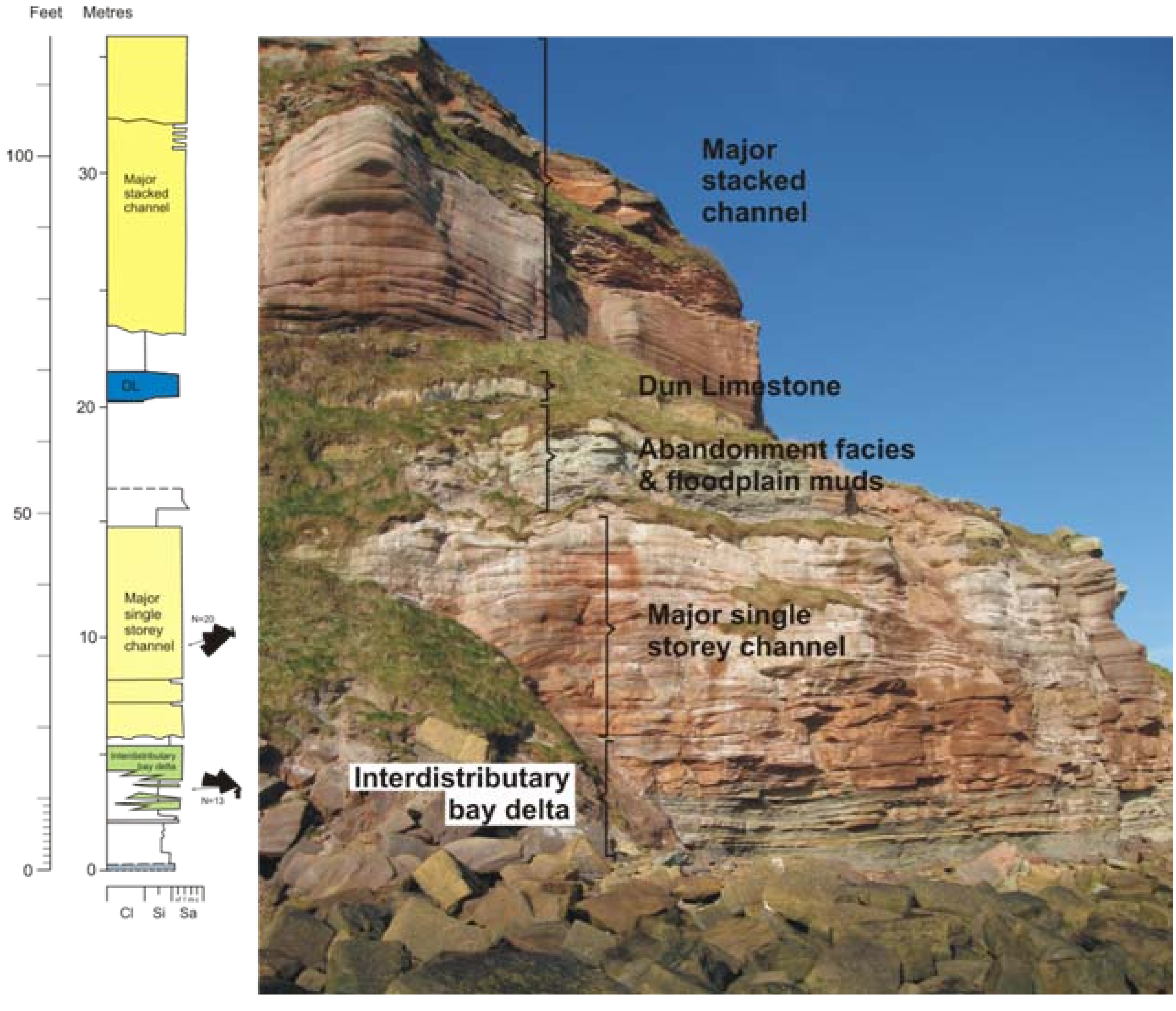


Figure 29. Photograph of the succession immediately above and below the Dun Limestone at the north-east end of Marshall Meadows Bay [NT 98180 57070]. Below the Dun Limestone, an upwards-coarsening interdistributary bay facies is erosively truncated by a major single storey channel. This fines upwards into muddy abandonment facies. Above the Dun Limestone a stacked major channel system is present.

Figure 30. Strandplain/barrier-island facies above the Doupster Oil-Shale. Two upwards-coarsening sandy lobes (marked SP) are separated by a bed of lagoonal muds. A set of asymptotic cross-bedding is arrowed. Red Shin, [NU 01629 50268].

Figure 31. Marine limestone facies, Dun Limestone (DL), overlying the Dun Coal (arrowed). As the outcrop is traced laterally up the cliff face the Dun Coal is progressively eroded by the overlying limestone. Marine mudstone can be seen overlying the Dun Limestone (top left). Huds Head, Spittal [NU 01269 50729].

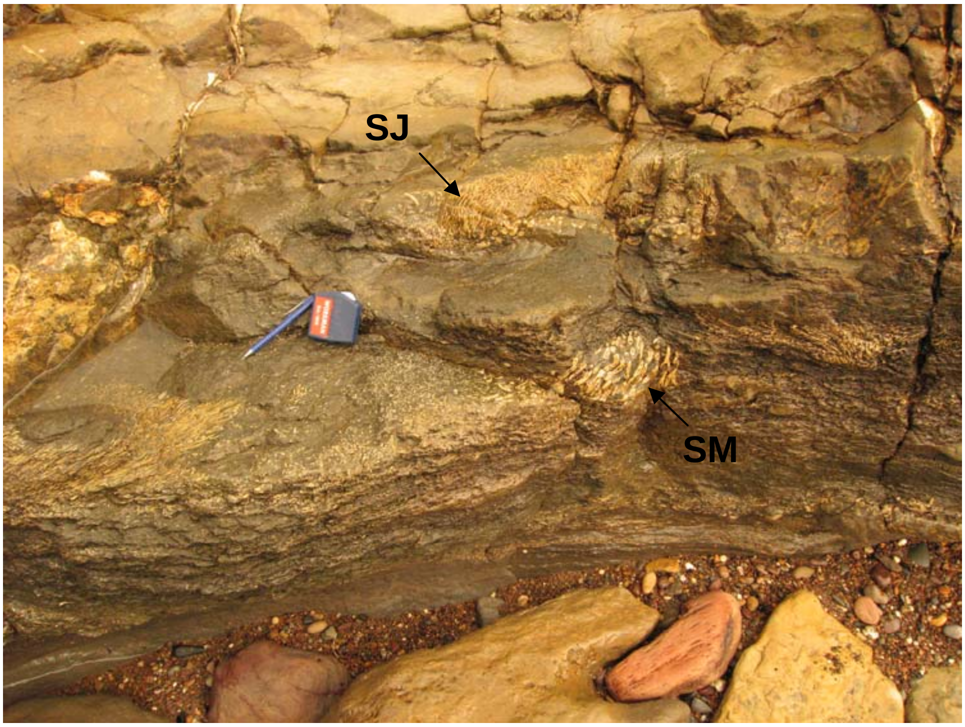


Figure 32. Marine limestone facies, comprising argillaceous limestone with common *Siphonodendron junceum* (SJ) and *Siphonodendron martini* (SM) corals. Woodend Limestone, The Skipper, Spittal [NU 01455 50499].

Figure 33. Marine mudstone facies, comprising laminated dark grey mudstones with siderite nodules. Succession immediately above the Dun Limestone at Huds Head, Spittal [NT 01269 50729].

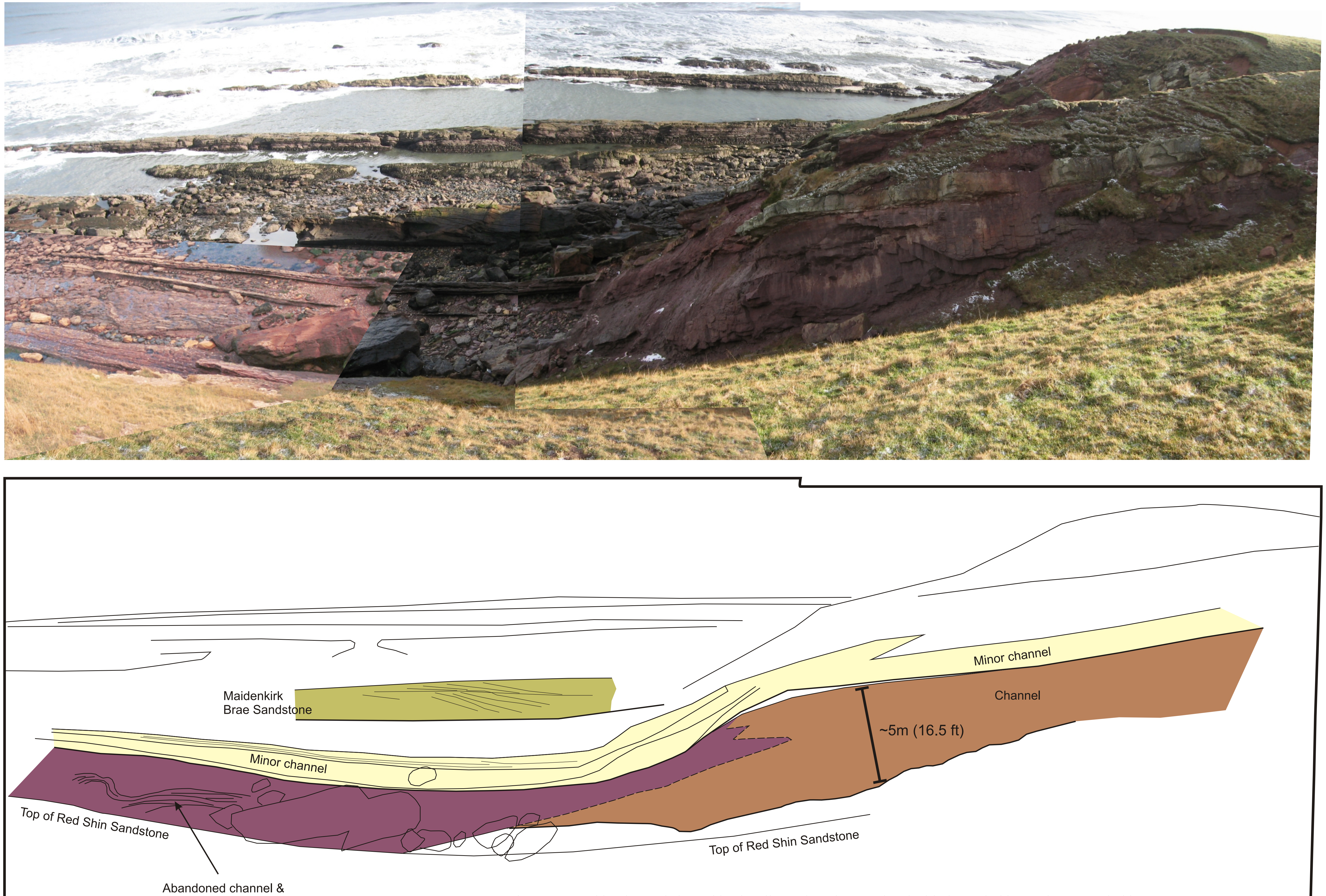


Figure 34. Muddy, slumped channel bank collapse deposits associated with the Red Shin Sandstone, Red Shin [NU 01699 50246]..

Figure 35. Slumped and burrowed sandy siltstone fill to abandoned channel plug. Minor heterolithic channel in succession below the Dun Limestone at Huds Head, Spittal [NU 01223 50785].

Figure 36. Burrowing in the upper part of a major channel sandbody. Tenquarter Freestone, A1167 road section, Springhill Reservoir [NU 00097 50611].

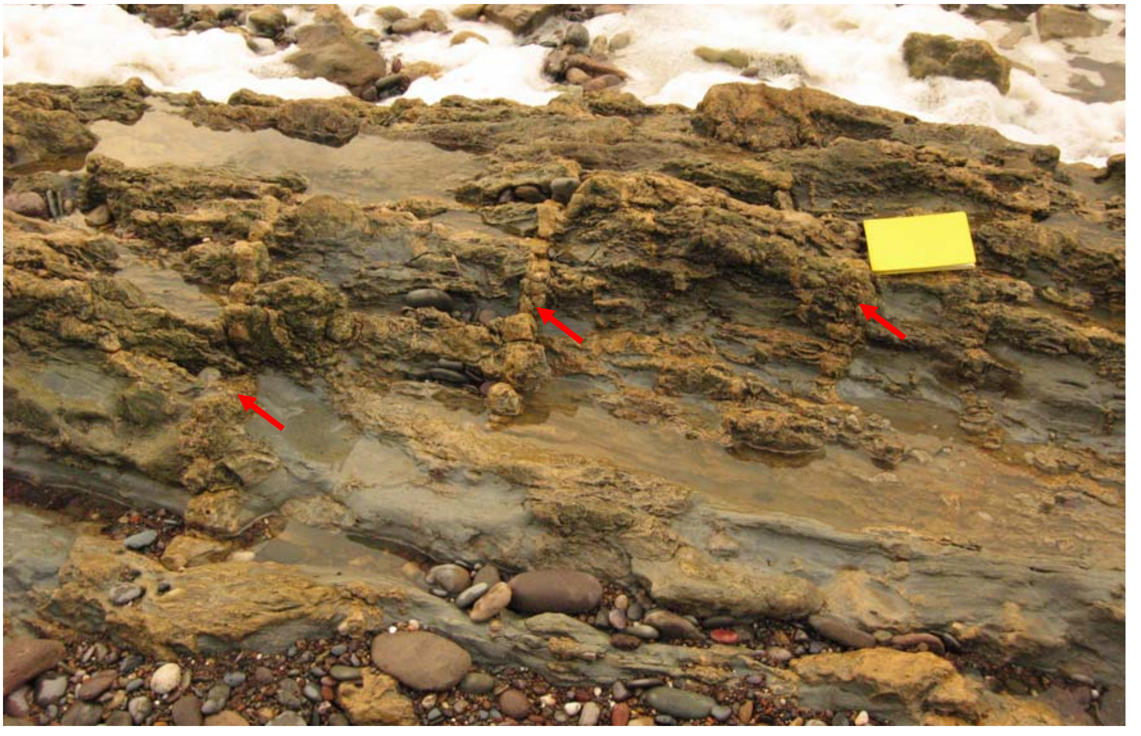


Figure 37. Calcrete palaeosol below the Woodend Limestone. Carbonate nodules form the prominent yellow brown irregular nodules, some of which are arrowed. The Skipper, Spittal [NU 01448 50500].

Figure 38. Grey alluvial palaeosol facies with vertical ironstone (siderite) nodules (arrowed). Huds Head, Spittal [NU01261 50714].

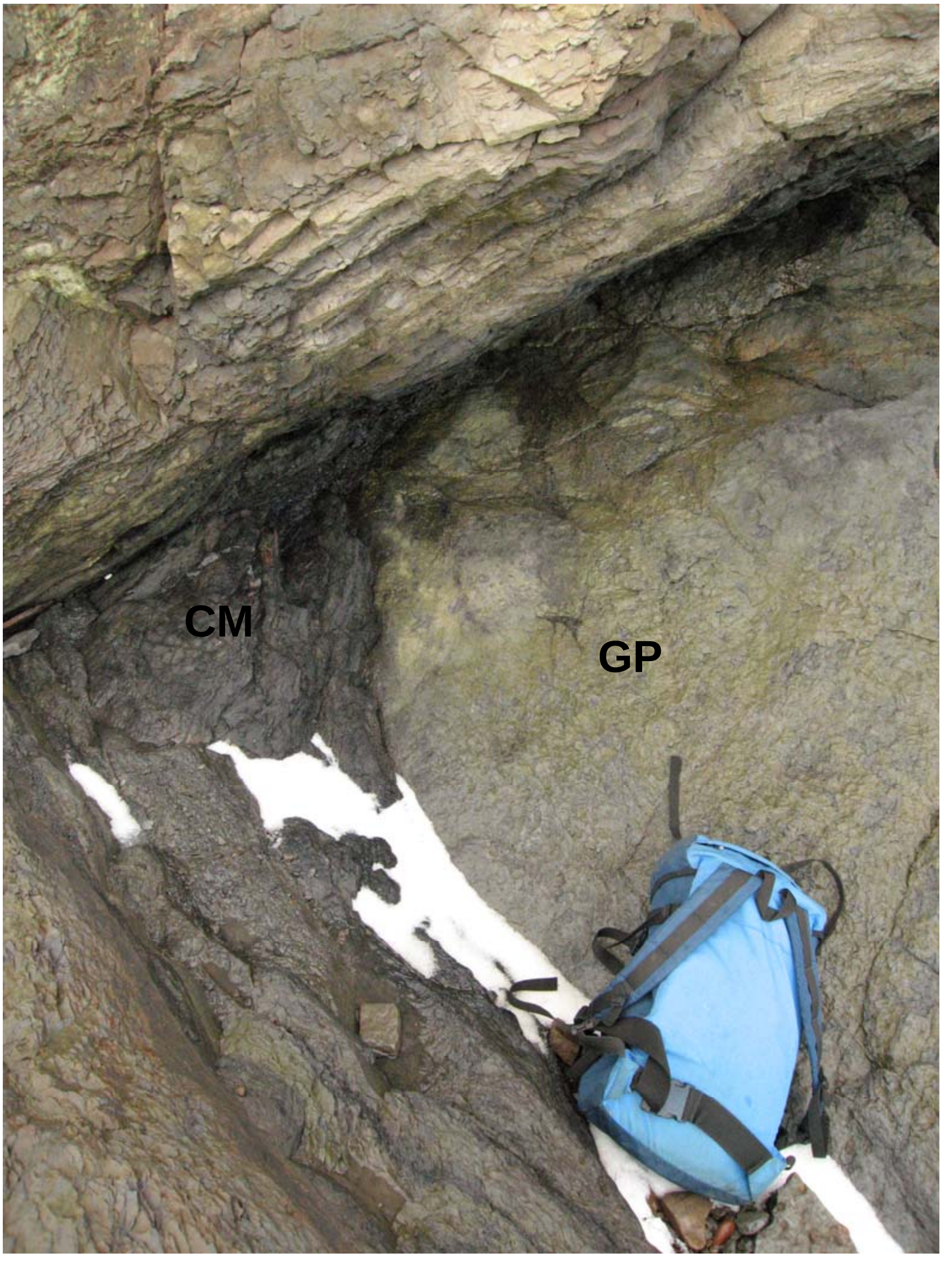


Figure 39. Gley palaeosol facies (GP) overlain by a coaly mudstone. Huds Head, Spittal [NU 01214 50769].

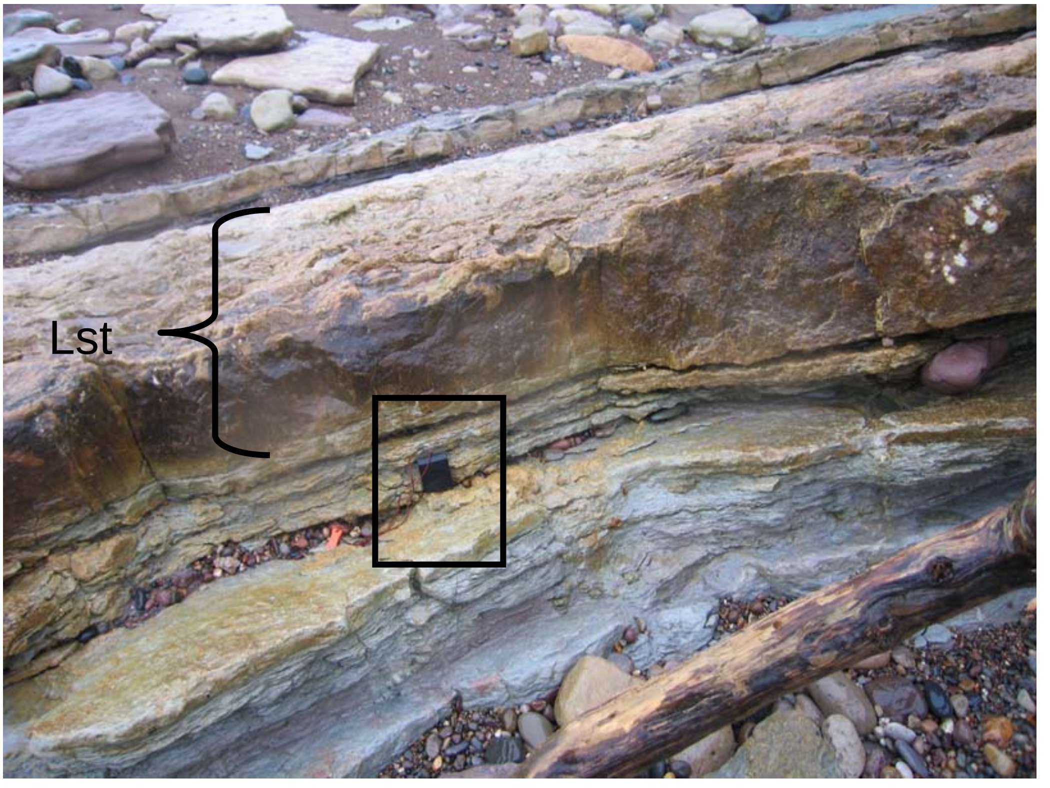


Figure 40. Lacustrine facies, comprising a lacustrine limestone, known as a cementstone. The compass clinometer for scale is 10 x 6 cm. Red Shin, Spittal [NU 01663 50261].

Figure 41. Lacustrine facies, comprising an algal bed (AB) of rounded oncolites and the Doupster Oil-Shale, forming the prominent bed of dark mudstone (arrowed). Red Shin, Spittal [NU 01663 50261].

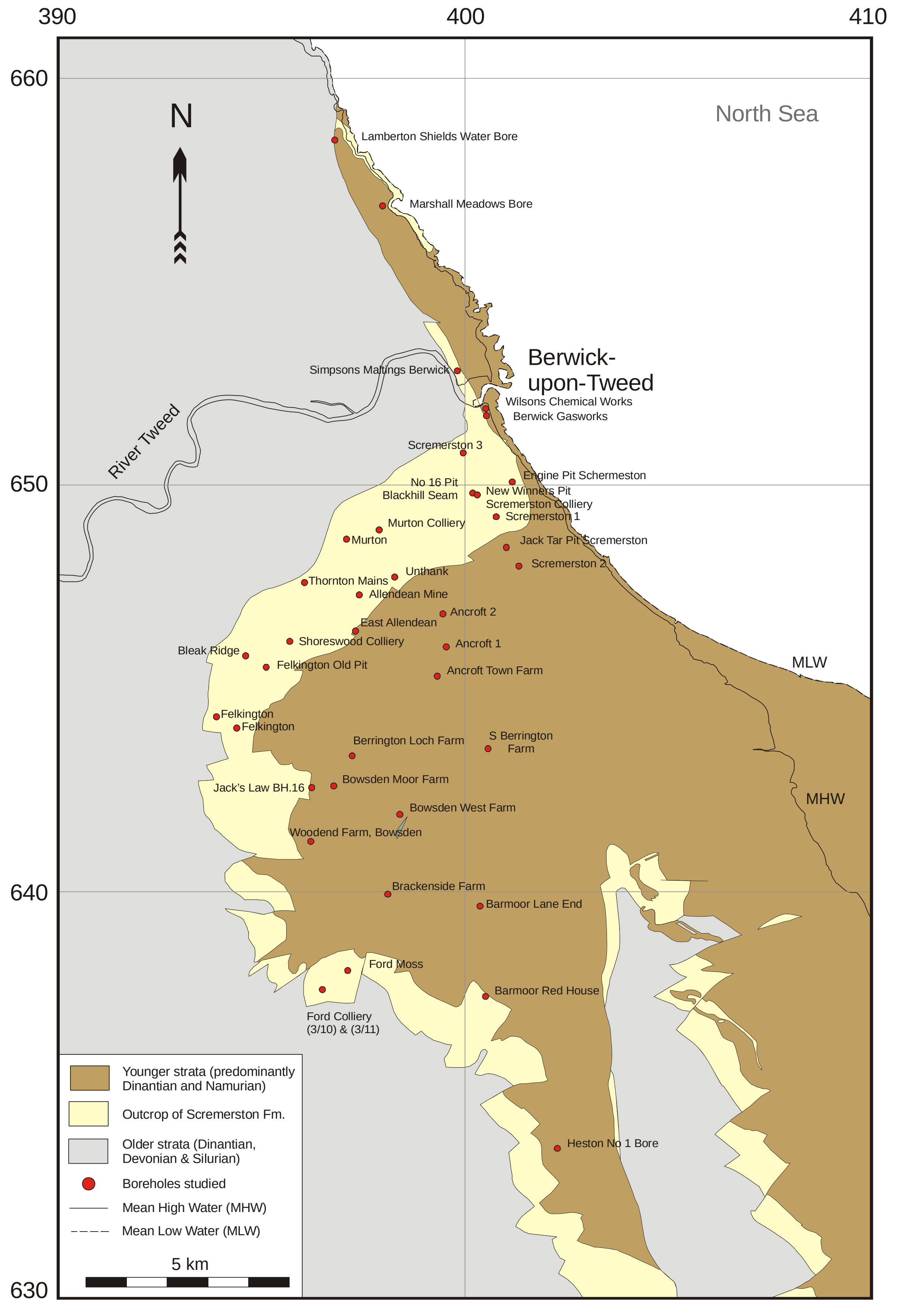


Figure 42. Map of the Berwick area to show the locations of the boreholes studied.

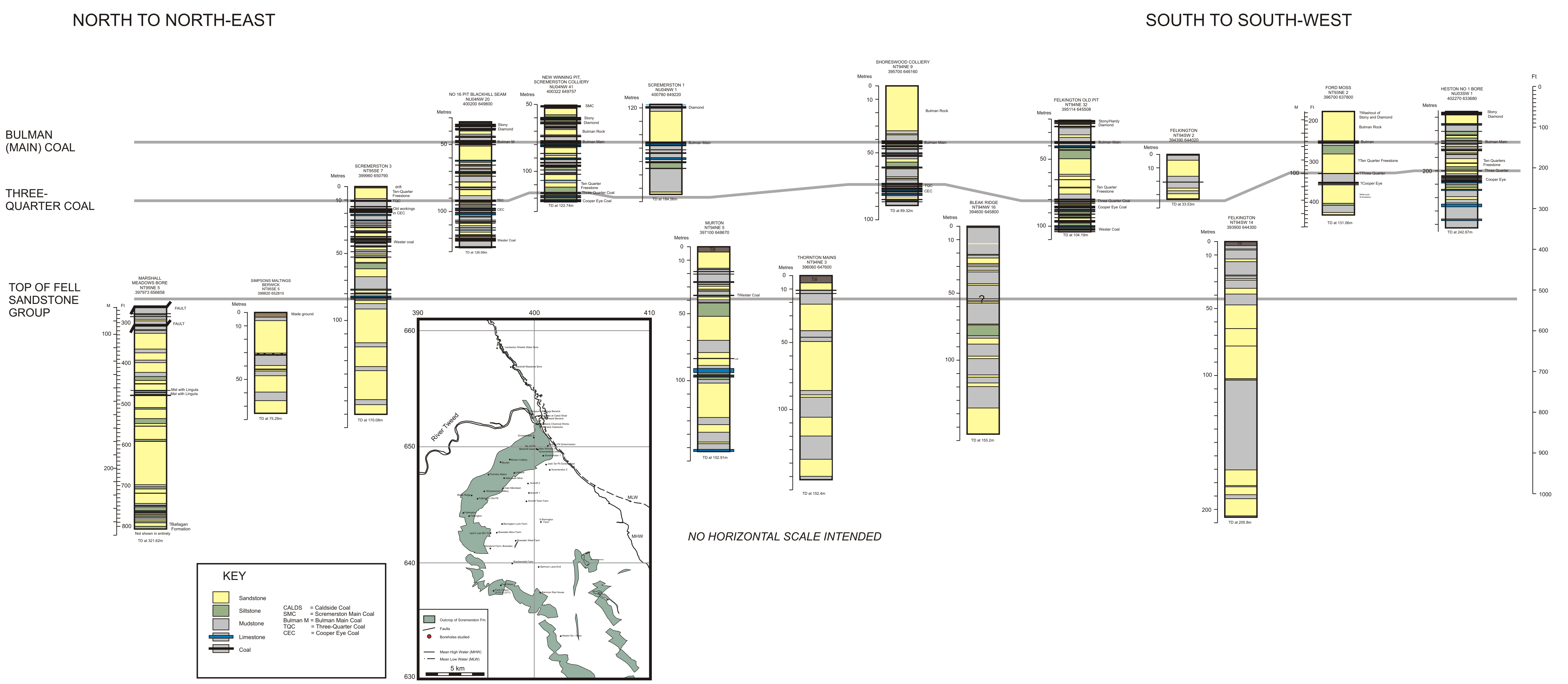


Figure 43. Borehole correlation through the upper part of the Fell Sandstone to lower part of the Scremerston Formation (Bulman Main Coal level) in the Berwick area of N.E. England.

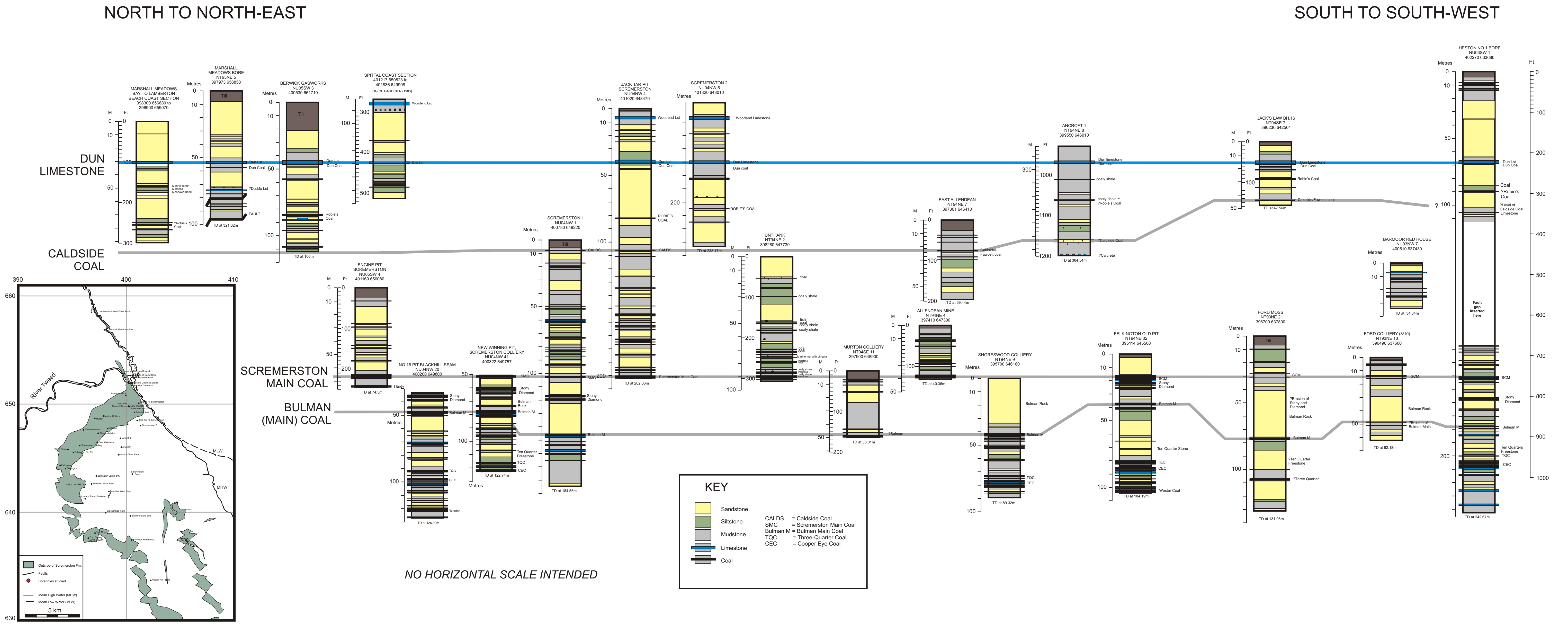


Figure 44. Borehole correlation through the upper part of the Scremerston Formation (Bulman Main Coal to Dun Limestone) in the Berwick area of N.E. England.

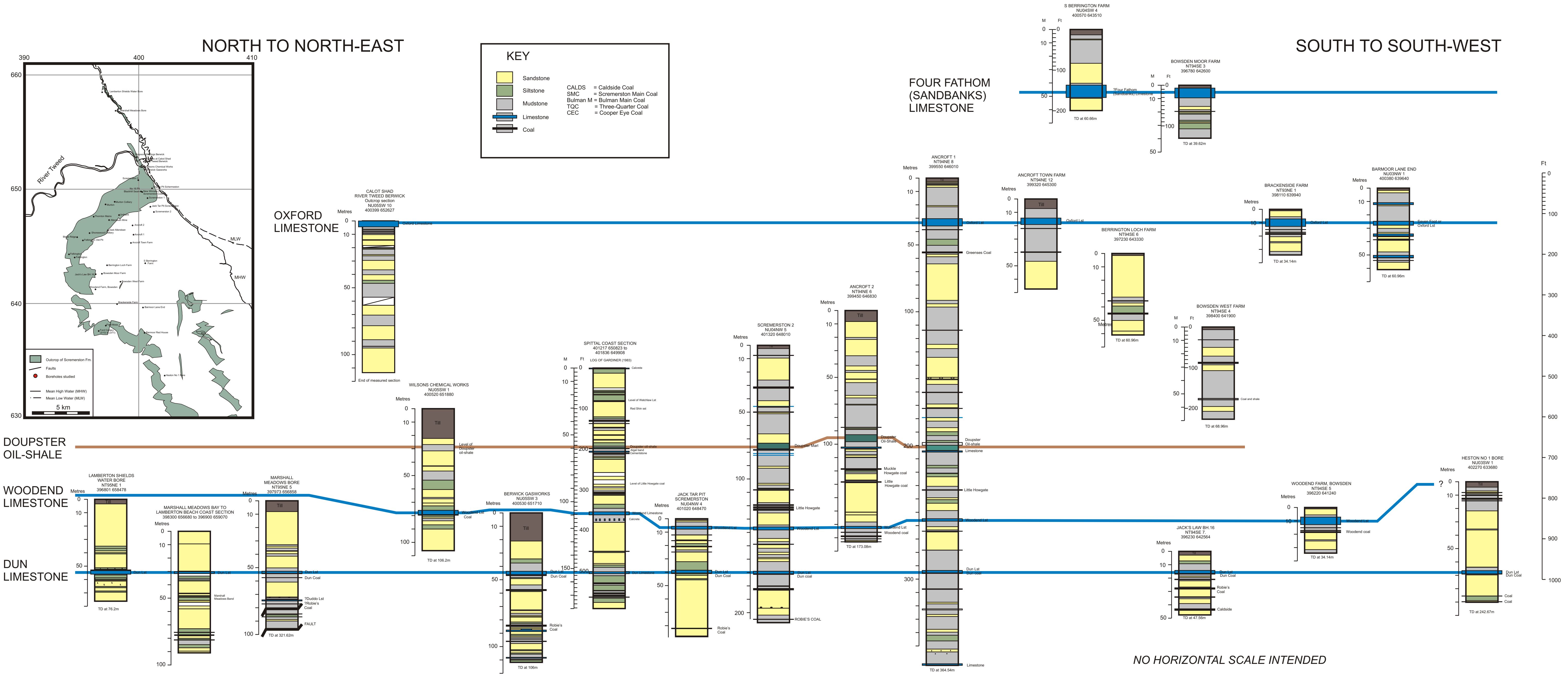


Figure 45. Borehole correlation through the upper part of the Scremerston Formation and lower part of the Yoredale Formation in the Berwick area of N.E. England.

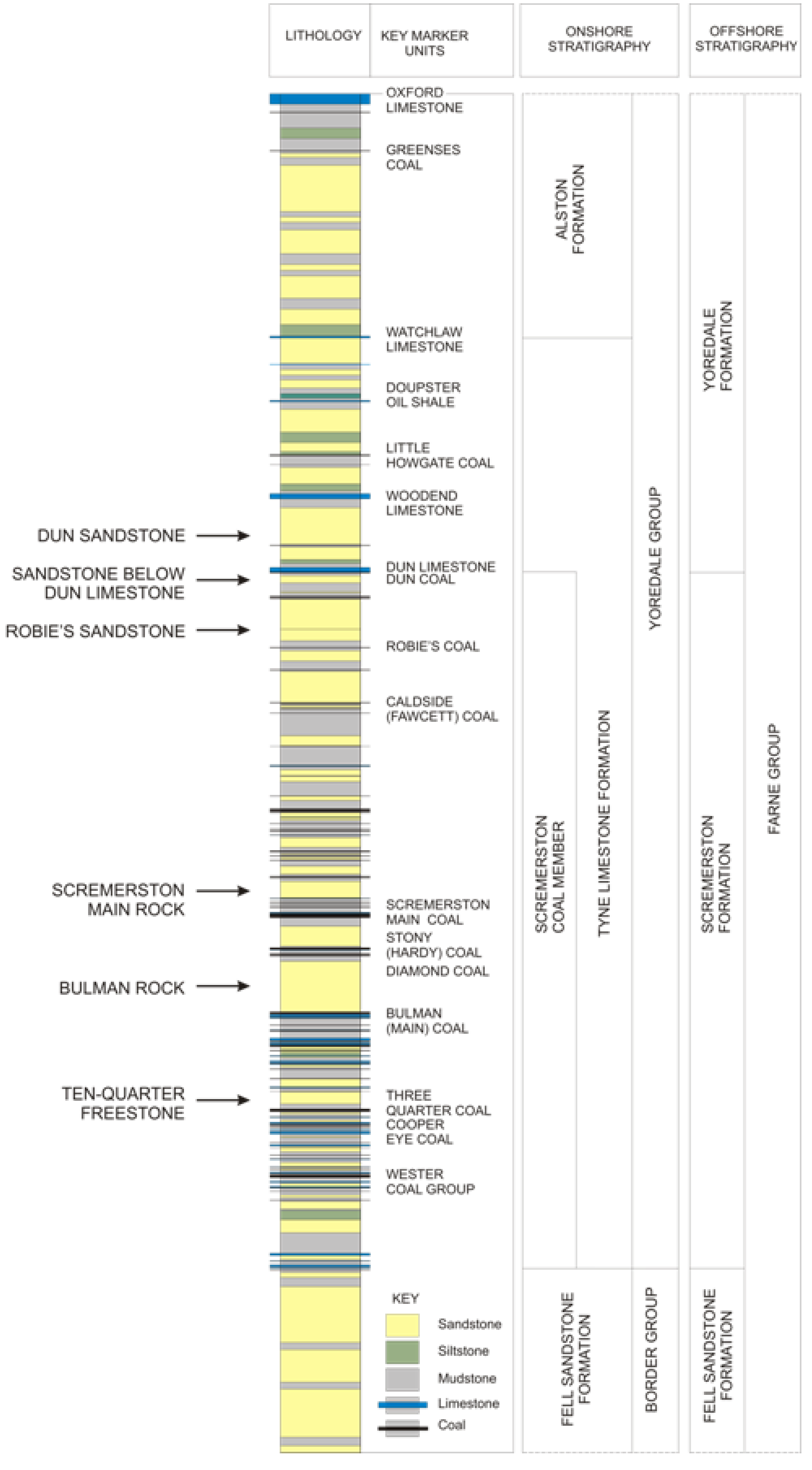


Figure 46. Generalised stratigraphy of the Scremerston Formation to show the sandbodies illustrated in the more detailed palaeogeography maps.

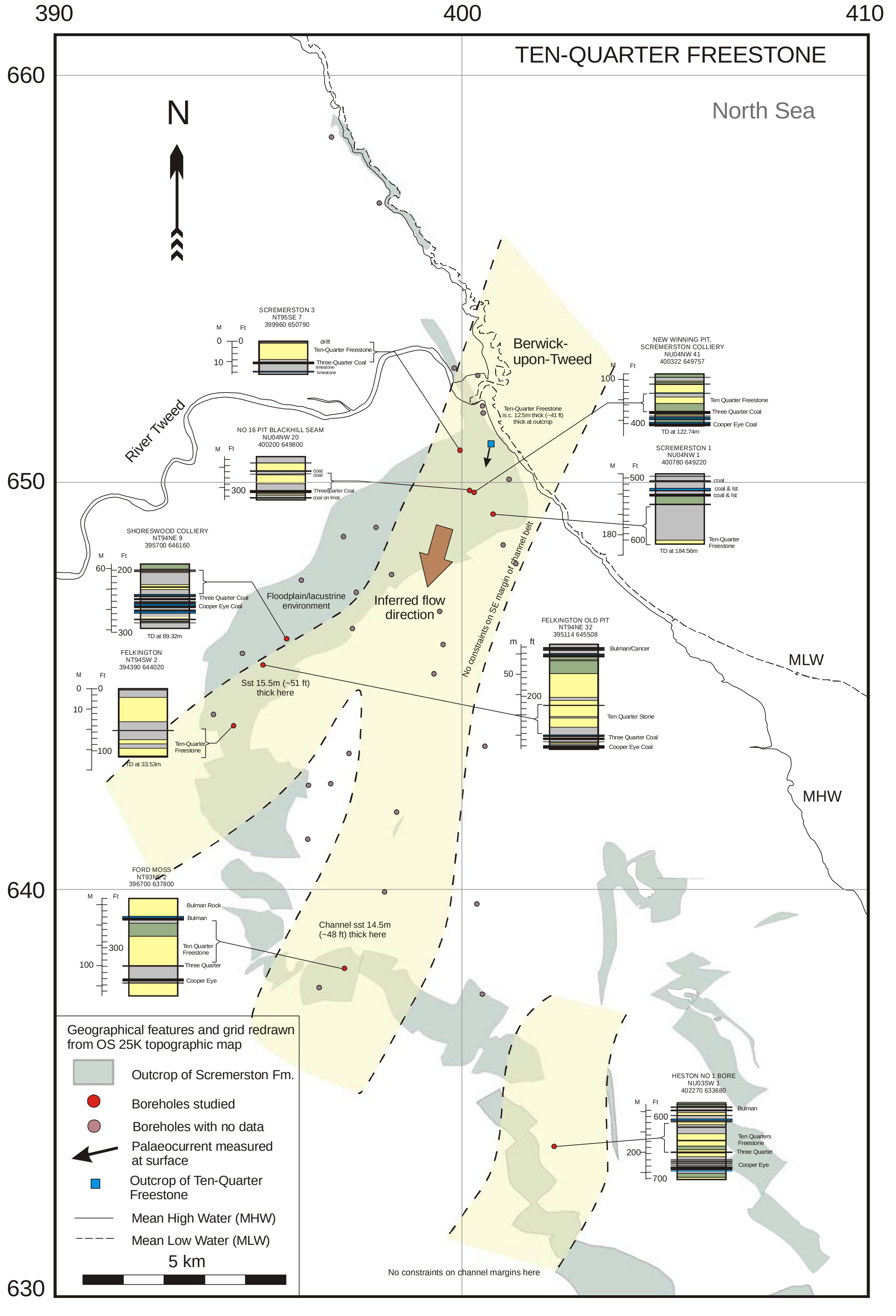


Figure 47. Schematic palaeogeography map to show the Ten-Quarter Freestone channels.

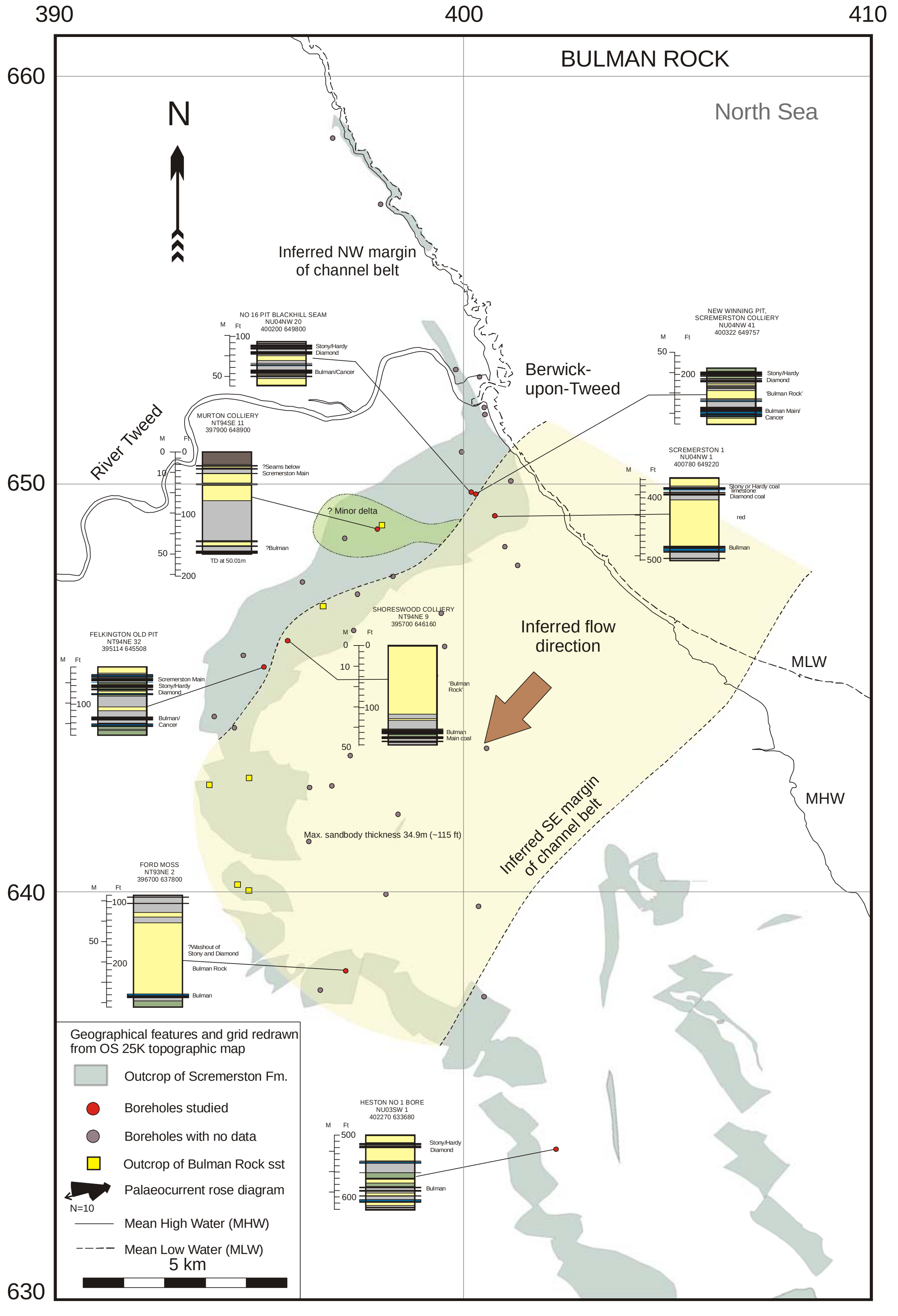


Figure 48. Schematic palaeogeography map to show the Bulman Rock channel.

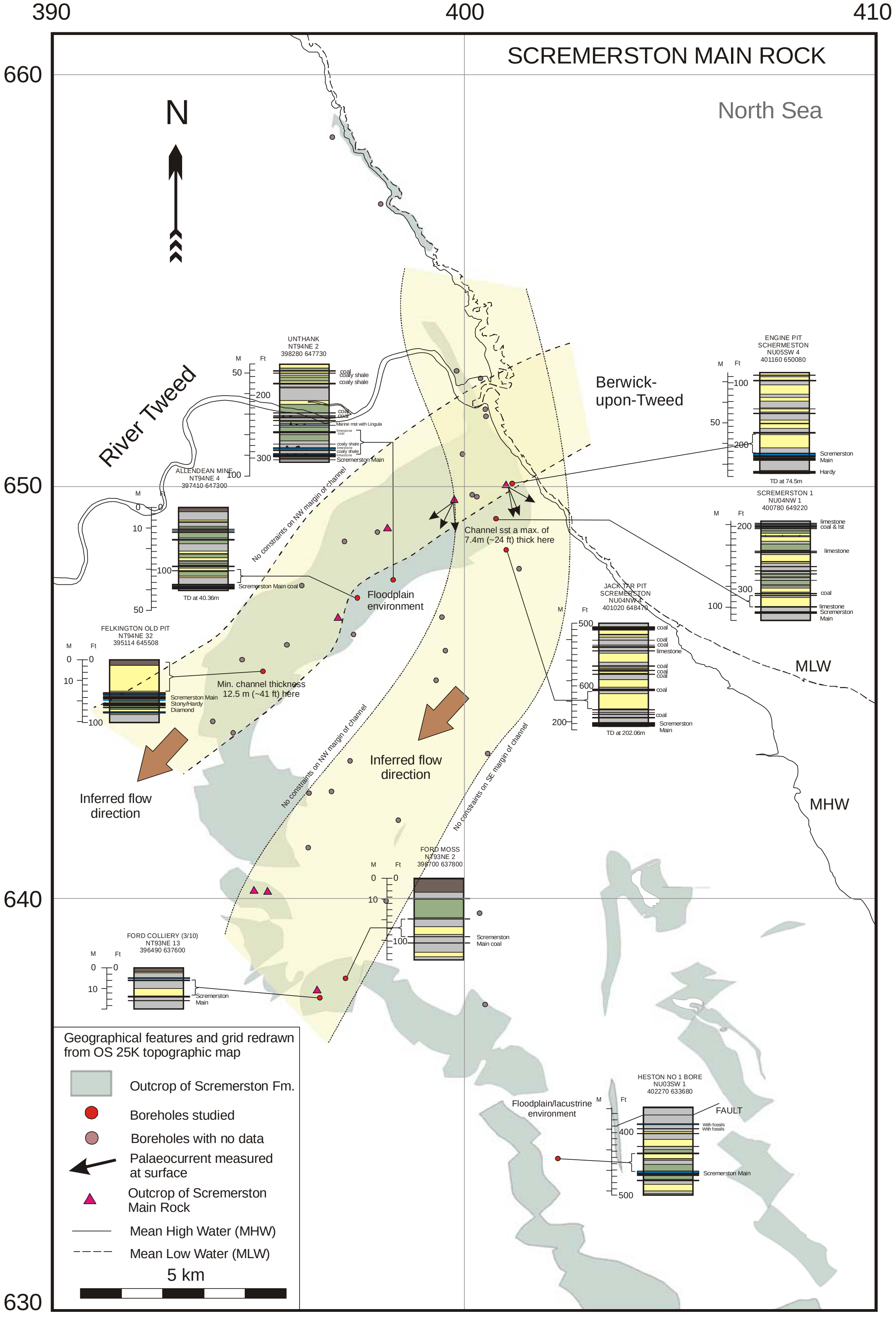


Figure 49. Schematic palaeogeography map to show the Scremerston Main Rock channels.

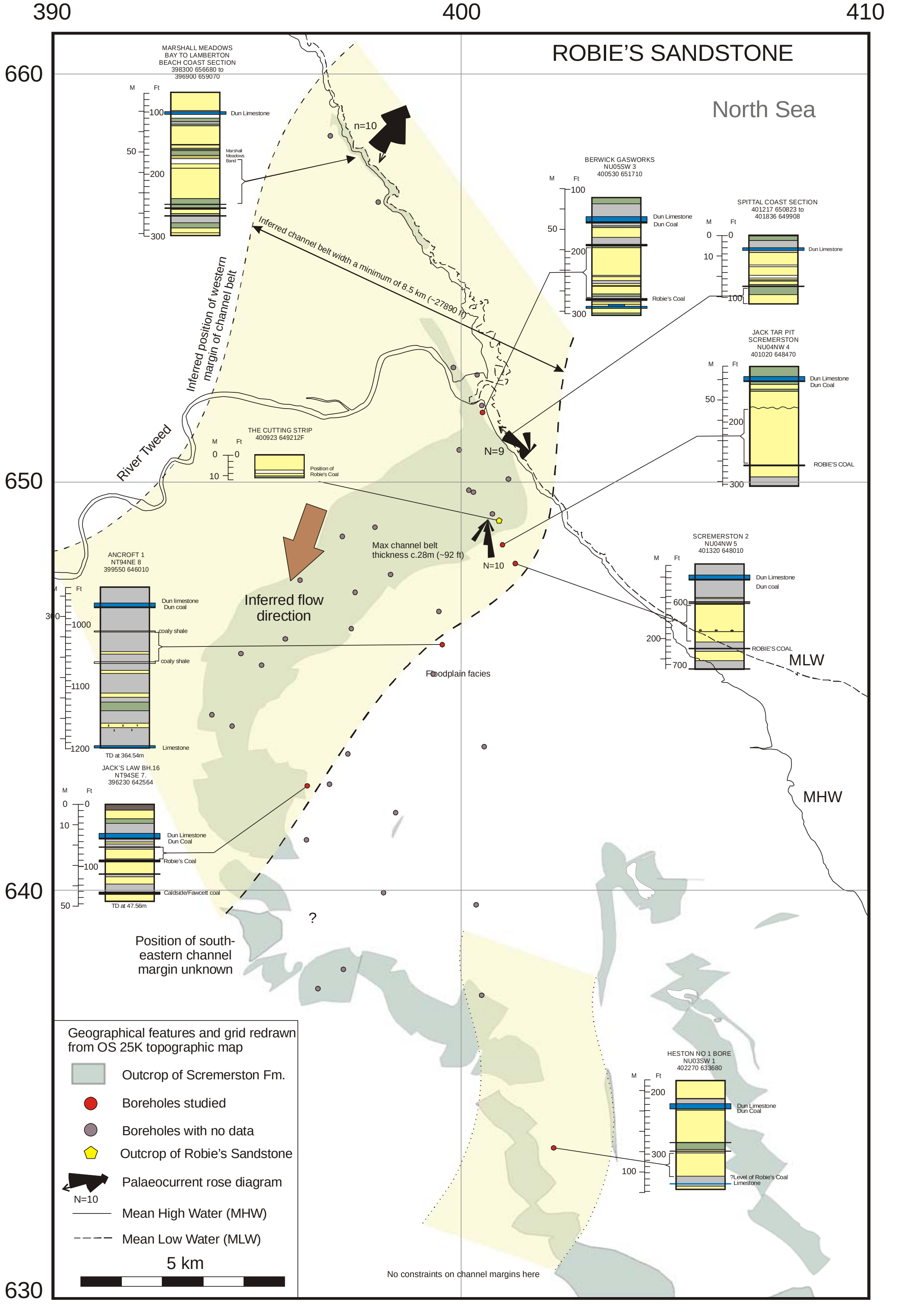


Figure 50. Schematic palaeogeography map to show the Robie's Sandstone channel.

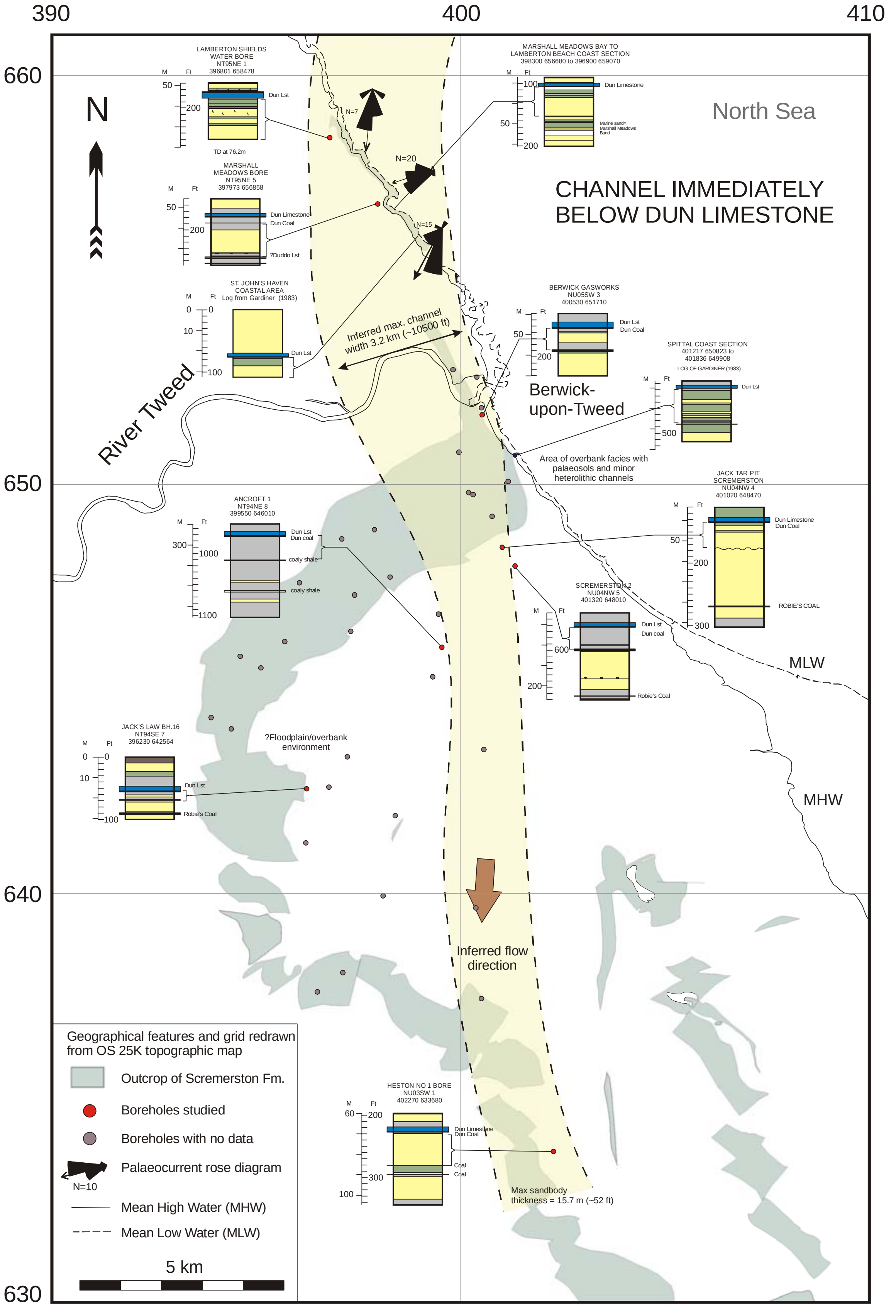


Figure 51. Schematic palaeogeography map to show the channel below the Dun Limestone.

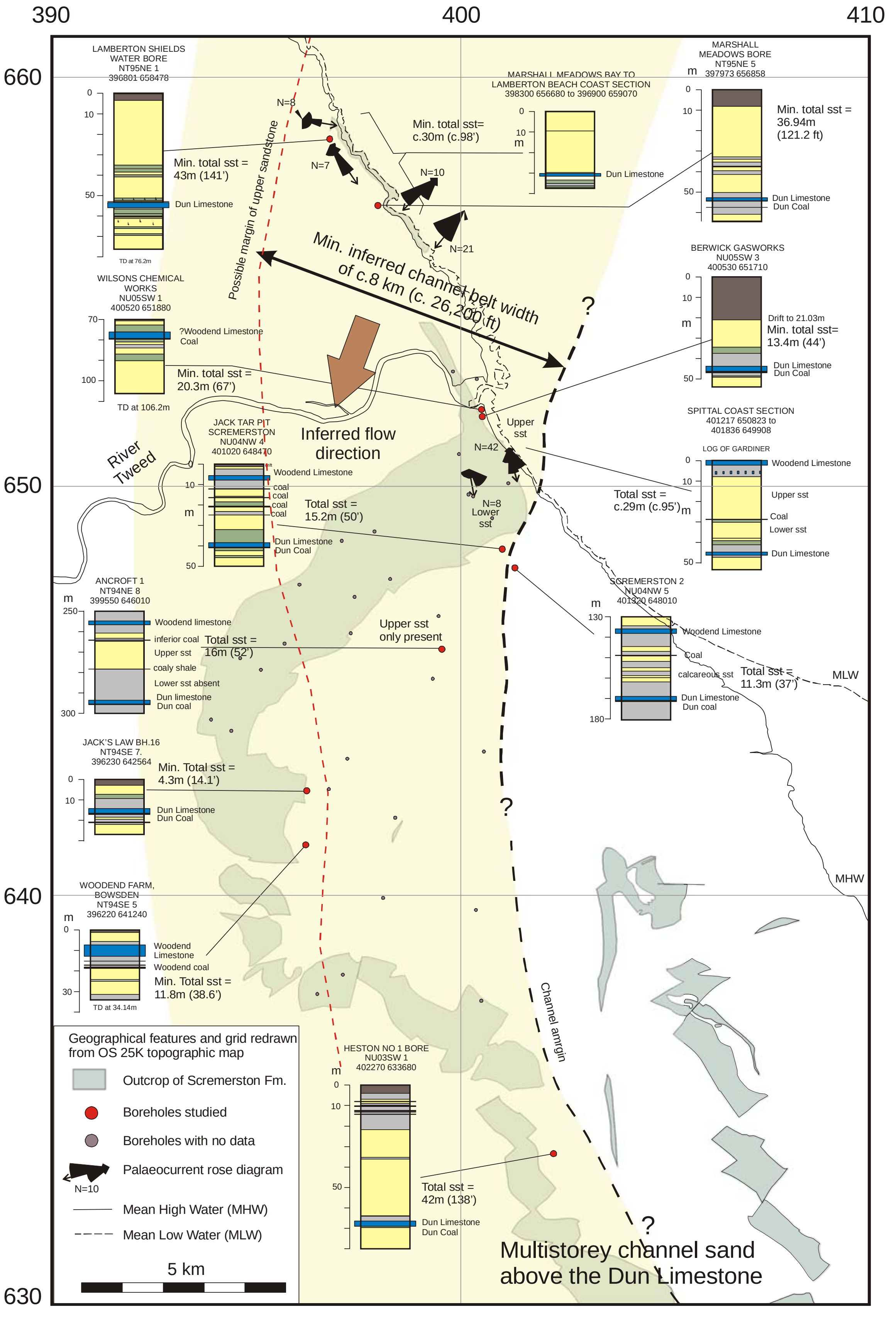


Figure 52. Schematic palaeogeography map to show the channel above the Dun Limestone.

Figure 53. Correlation panel to show the facies above and below the Dun Limestone in the area around Marshall Meadows Bay. Reproduced, with modifications, from Gardiner (1983).

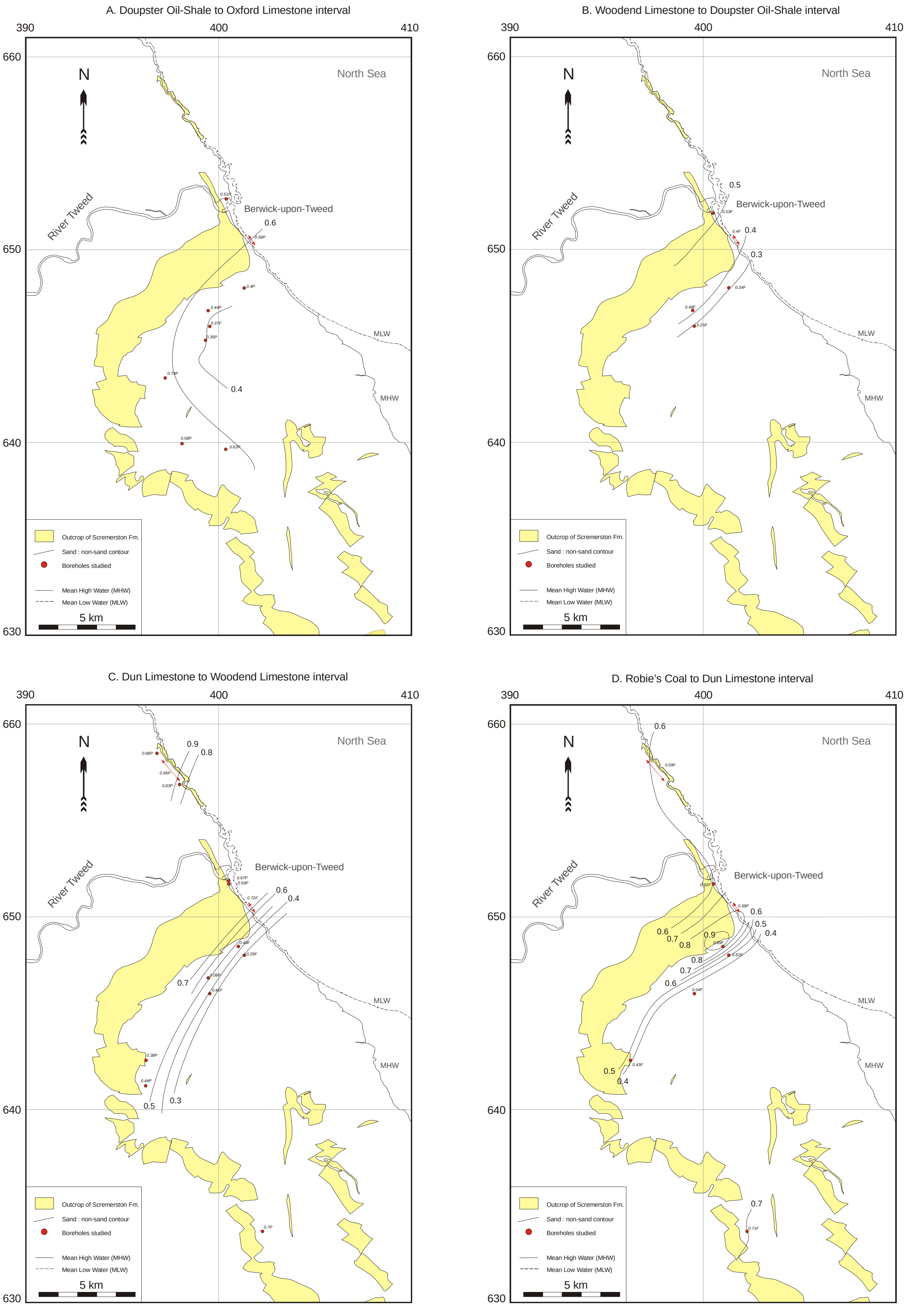


Figure 54. Sand-to-non-sand maps for a number of stratigraphic intervals in the Scremerston and Yoredale formations.

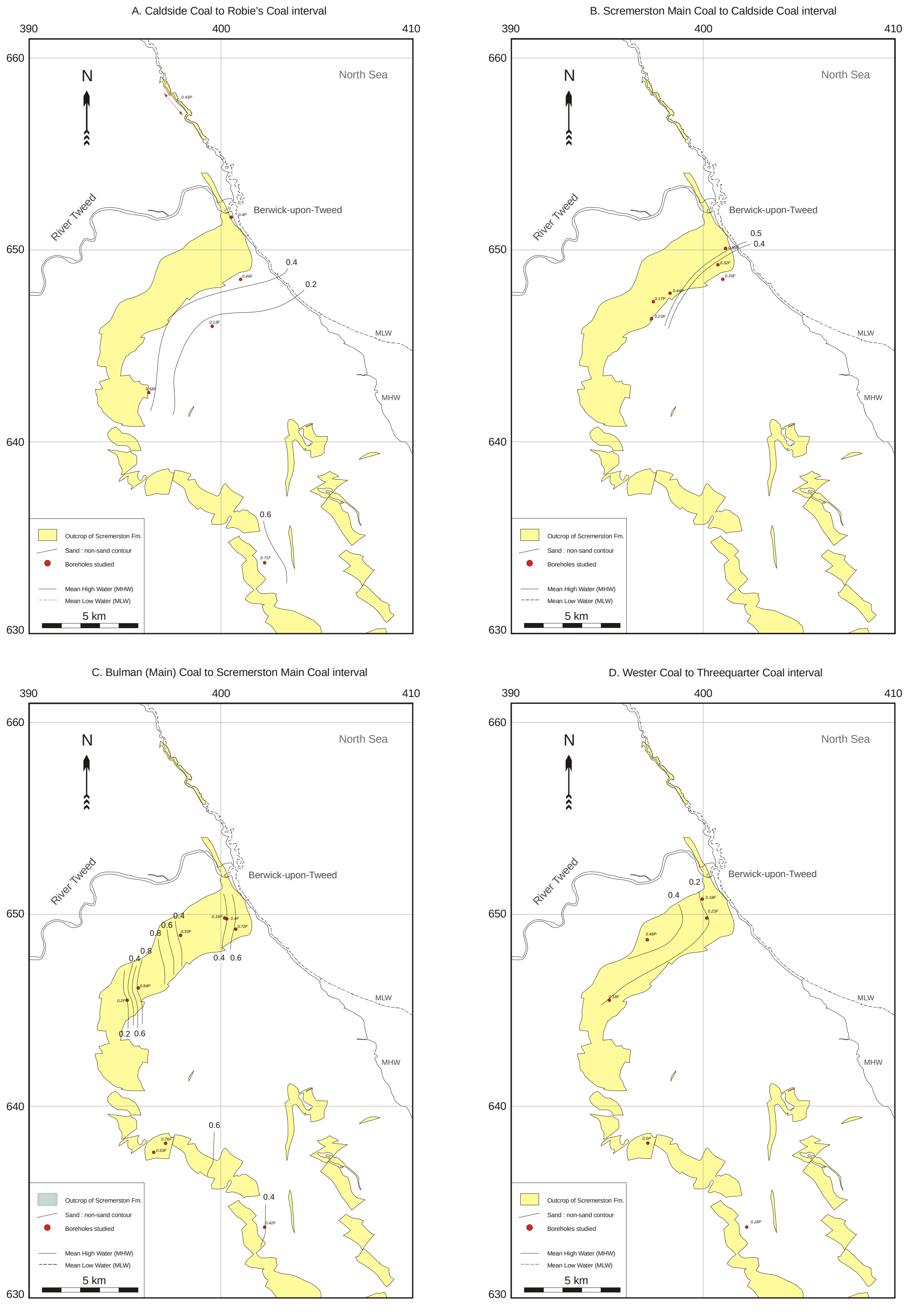


Figure 55. Sand-to-non-sand maps for a number of stratigraphic intervals in the Scremerston Formation.

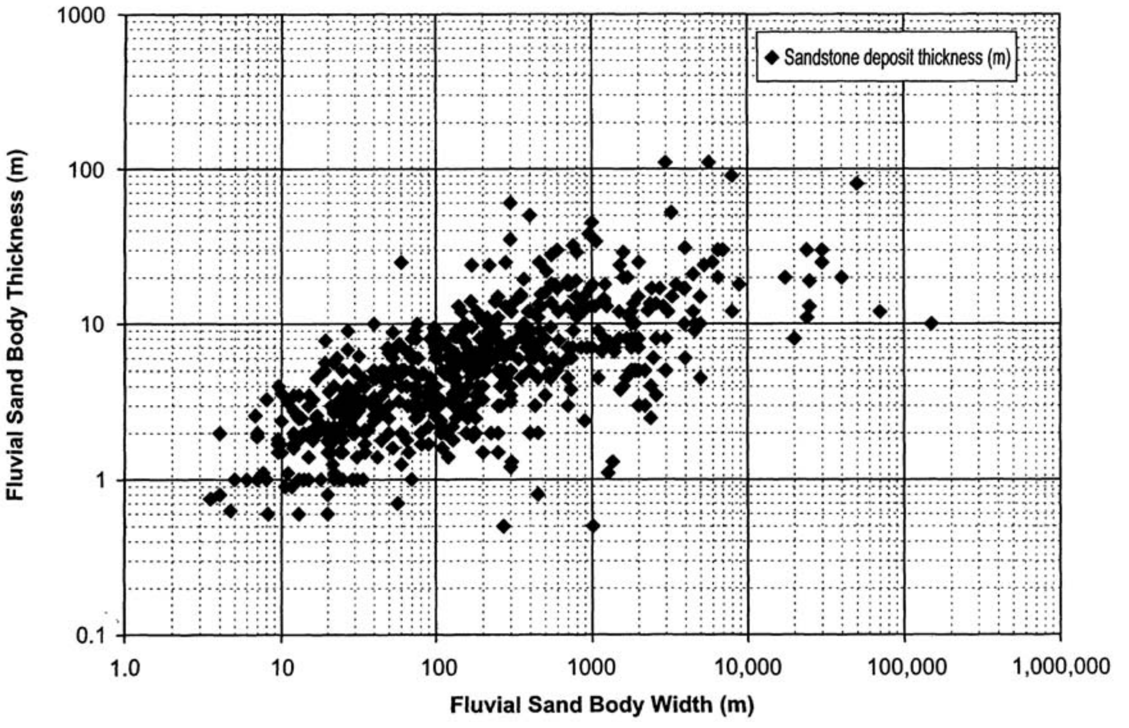


Figure 56. Log-log cross-plot of thickness versus width for fluvial sandbodies. This is reproduced from Shanley (2004) and represents a dataset of 595 fluvial sandbodies, largely derived from outcrop descriptions from the geological literature.

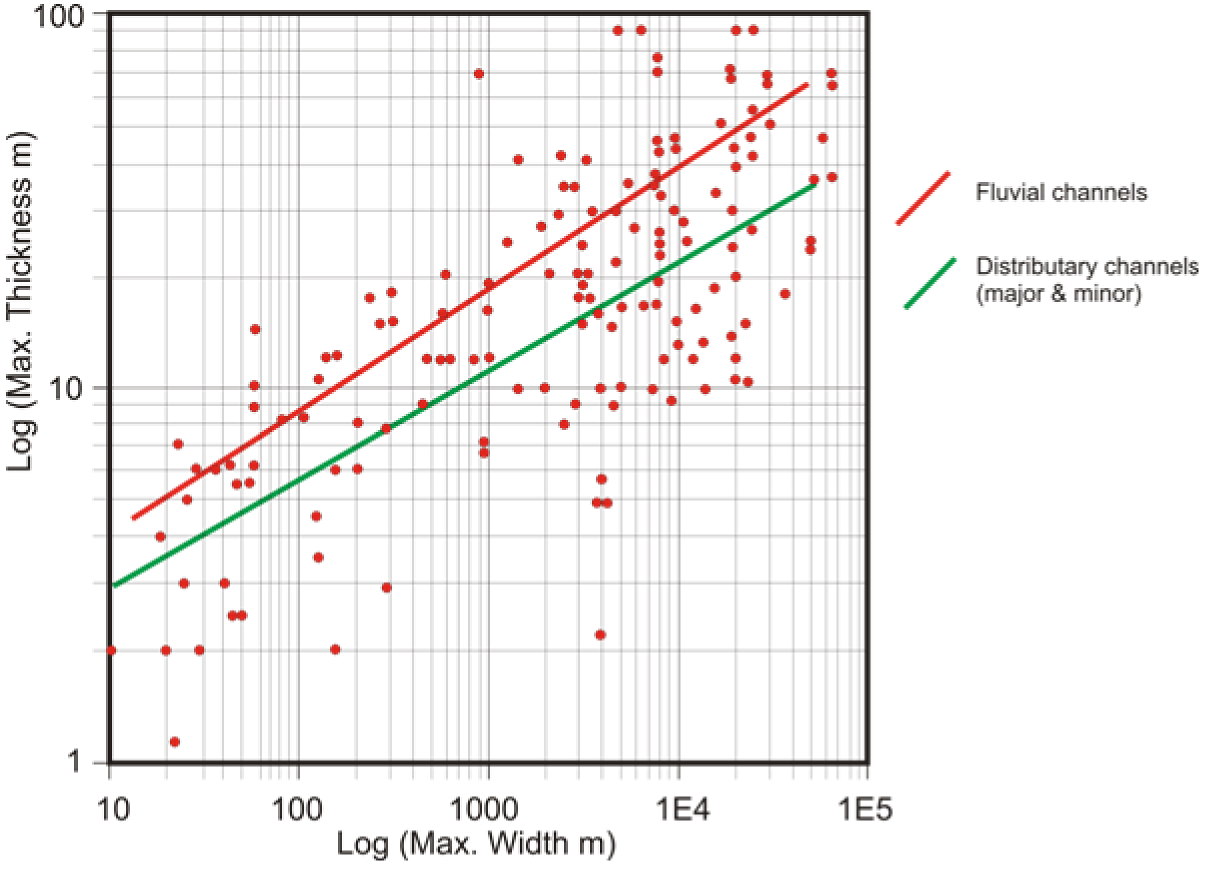


Figure 57. Cross-plot of Carboniferous sandbody thickness versus sandbody width. Taken from outcrop analogue data (redrawn from ECL 1990).

FACIES ASSOC-IATION	FACIES	DESCRIPTION	INTERPRETATION	TYPICAL THICK-NESS
Channel	Major Stacked Channel	Fine to coarse-grained sandstone, grey to brown; pebbly to conglomeratic in places, comprising predominantly rounded extraformational (quartz) pebbles, some grey mudstone clasts. Poorly to moderately sorted, subangular to subrounded grains, some visible porosity. Trough and planar-tabular cross-bedding in sets up to a few feet thick; erosively based	Represents deposition in a large, deep river channel. Flows generally within the lower flow regime capable of transporting up to pebble grade detritus. Cross-beds represent the deposits of subaqueous dunes	Approx 48ft (14.5m)
	Channel abandonment	Sandstone, sandy siltstone & silty claystone; interbedded; dark grey & brown, sandstone is fine- to medium-grained, common vertical & horizontal burrows including *Diplocraterion* , ?*Skolithos* & ?*Teichichnus* , well cemented by siderite, common plant debris, micaceous & pyritic in parts. Marine fauna includes productoid brachiopod spines and nuculoid bivalve fragments	Represents the fill of an abandoned channel. Marine influence is indicated by the fauna and trace fossil assemblage. This suggests that the channel was connected to the marine environment and transgression accompanied sedimentation. The pervasive siderite cement suggests slow sedimentation rates	~1.5 ft (~0.5 m)
Open marine	Marine	Silty claystone; grey to dark grey, parallel laminated, some siderite and hematite (?after siderite) nodules, rare burrows, rare sandy and/or silty laminae, marine fauna including bivalve and brachiopod fragments and *Lingula*	Deposition from suspension in an open marine setting. The presence of marine fauna indicates normal or near normal salinity. Sandy laminae deposited by periodic input of coarse detritus. Siderite is uncommon in marine sediments and its presence here may indicate either the exhaustion of sulphides coupled with high dissolved carbonate under conditions of low eH or a later diagenetic phase	3 - 9 ft (~0.9 - 2.7 m)
Interdis-tributary	Prodelta	Silty claystone and siltstone, grey, occasionally red, generally forms the lower part of upwards-coarsening succession. Parallel laminated siltstone dominant. Rare very fine-grained silty sandstone, present as wave and current rippled lenses and thin laminae, micro-micaeous, some plant debris	Represents the most distal (prodeltaic) part of a delta. Facies progradation is indicated by the upwards-coarsening nature and by the occurrence of more proximal facies above. Laminated siltstones were deposited from suspension and weak tractional currents. Lenses and laminae of sand represent suspended-sediment-laden currents or low density underflows which were subjected to wave and current reworking. Deposition into a marine environment likely	2 - 4 ft (~0.6 - 1.2 m)
	Interdistrib-utary bay delta	Forms an overall upwards-coarsening succession. Comprises sandstone and silty sandstone, minor siltstones; interbedded, grey to light brown, Sandstones are fine- and medium-grained, moderately to well sorted where sandy, poorly sorted where admixtures of sand and silt occur. Lower part tends to contain greater silt, with common wave ripples, small scale load structures and convolute lamination, common sandy and silty laminae and lenses. Upper part is sand dominant, with common trough cross-bedding, some current ripples and less common wave ripples. Simple subvertical burrows in places. Common mica and plant debris. Bed boundaries sharp or gradational. Commonly either rooted at top or overlain by marine facies	Represents the deposits of a shallow water delta which prograded into an interdistributary bay. The lower silty part represents the deposits of the sloping margin of the advancing delta front and the upper sandy part represents the area of shoaling associated with the termination of a feeding distributary channel. Deposition into a marine environment likely; salinity may be full or possibly reduced due to the influx of fresh water. Deposition took place from bedload-transporting tractional currents that flowed down the delta front, generating ripples; these were reworked by waves in the lower part of the delta. The delta top was either emergent and colonised by plants or flooded during a subsequent sea-level rise	11 ft (3.4 m)
	Minor crevasse delta	Siltstone, sandy siltstone and sandstone forming a minor coarsening-upwards succession. Dark grey to reddish brown. Sandstone is very fine- to fine-grained, poorly sorted, common wave and current ripple cross-lamination with silty foresets and drapes, some wavy and parallel lamination. The upper part of the succession comprises small scale cross-bedding. Sandier intervals have sideritic cement, are micaceous, contain some plant debris, and have simple horizontal and vertical burrows. Commonly rooted at the top	The upwards-coarsening nature of the succession suggests the progradation of a delta system. However, the reduced thickness, when compared with other delta deposits, suggests that deposition was confined to a shallow water setting. Wave and current reworking processes were obviously important and this, together with the presence of burrowing, suggests that an interdistributary bay environment may be likely. Rooting at the top indicates infilling of the bay and delta abandonment	5 - 8 ft (~1.5 - 2.5m)
	Crevasse splay complex	Facies typically comprises beds of sandstone, with minor interbedded silty sandstone and siltstone. Sandstone beds are typically sharp-based and sharp topped, fine-grained, grey and brown, cross-laminated and parallel laminated, common simple horizontal burrows (?*Planolites*), possible *Teichichnus* and *Thalassinoides* burrows. Succession typically rooted in upper half	Sharp based and topped beds of sandstone form from episodic, unconfined waning sheet-flood events, interpreted as crevasse splay events. These originated as a product of breaching or crevassing of a distributary channel bank, allowing floodwater from the channel to flow into the interdistributary setting. Sands were deposited from unconfined, turbulent flow carrying a dominantly sandy bedload. A marine connection is indicated by the trace fossil assemblages, hence deposition in an interdistributary bay setting is proposed	4 ft
Palaeosol	Mire	Coal and coaly mudstone; coal is black and contains common dark grey mudstone laminae. Coal is predominantly vitrain. Coaly mudstone comprises dark grey to black mudstone with common bright coal laminae. Some weathered pyrite (?jarrowsite) present	Coals are interpreted to have formed from the autochthonous deposition, burial and coalification of organic material. This organic material formed in shallow, submerged peat-forming mires which developed on abandoned channels and on infilled sediment surfaces. The high ash (=siliciclastic sediment) indicates that these were probably rheotrophic swamp deposits, These are a type of mire characterised by regular flooding, that are fed by groundwater and have flat-lying tops	Up to about 2 ft (~0.6m)
	Gley palaeosol	Rooted beds of silty claystone, siltstone and sandy siltstone. Common roots and plant debris, grey, typically massive due to the effects of pedoturbation, occasional reddened siderite nodules. Gradational base	Palaeosols are produced by the modification of other depositional facies by pedogenic processes. This type of palaeosol is interpreted as a gleysol that accumulated under poorly drained, reducing conditions. This is indicated by the common preservation of organic material and the presence of siderite nodules	Up to about 3 ft (~0.9 m)

Table 1. Sedimentary facies recognised from Cores 1 – 3 of Well 42/13-2.