Palaeoenvironment of braided fluvial systems in different tectonic realms of the Triassic Sherwood Sandstone Group, UK

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Abstract

Fluvial successions comprise the fill of sedimentary basins in a variety of tectonic realms related to extensional, compressional and strike-slip settings, as well as on slowly subsiding, passive basin margins. A major rifting phase affected NW-Europe during the Triassic and resulted in the generation of numerous sedimentary basins. In the UK, much of the fill of these basins is represented by fluvial and aeolian successions of the Sherwood Sandstone Group. Additionally, regions that experienced slow rates of Mesozoic subsidence unrelated to Triassic rifting also acted as sites of accumulation of the Sherwood Sandstone Group, one well-exposed example being the East England Shelf. The fluvial stratigraphic architecture of deposits of the Sherwood Sandstone Group of the East England Shelf (shelf-edge basin) is compared with similar fluvial deposits of the St Bees Sandstone Formation, East Irish Sea Basin (half-graben). The two studied successions represent the preserved deposits of braided fluvial systems that were influenced by common allogenic factors (e.g. climate, sediment source, delivery style); differences in preserved sedimentary style principally reflect the different tectonics settings. Analysis of lithofacies and architectural elements demonstrates that both studied successions are characterised by amalgamated channel-fill elements that are recorded predominantly by downstream-accreting sandy barforms. The different tectonic settings in which the two braided-fluvial systems accumulated exerted a dominant control to dictate

preserved sedimentary style and long-term preservation potential. In the East England Shelf, the vertical stacking of pebbly units and the general absence of fine-grained units reflects a slow rate of sediment accommodation generation (11 m/Myr). In this shelf-edge basin, successive fluvial cycles repeatedly rework the uppermost parts of earlier fluvial deposits such that it is only the basalmost channel lags that tend to be preserved. By contrast, in the East Irish Sea Basin of West Cumbria, the rate of sediment accommodation generation was substantially greater (95 m/Myr) such that space was available to preserve complete fluvial cycles, including silty drape units that cap the channelized deposits.

Key words: Fluvial, tectonics, lithofacies, architectural elements, stacking pattern

1. Introduction

The preserved sedimentary architecture of fluvial successions is known to vary as a function of tectonic setting, notably basin type and subsidence rate (Bridge 2003, 2006; Weissmann et al., 2010; Colombera et al., 2013). Fluvial successions are well documented as the fill of sedimentary basins characterized by extensional tectonics in rift and intermontane settings (e.g. Leeder et al., 1996; Cavinato et al., 2002; Ghinassi et al., 2009; Maspeizer, 2013, Gombo et al., 2014; Santos et al., 2014), in transtensional pull-apart basins (e.g. Hempton and Dunne, 1994; Gruber and Sachsenhofer, 2001), and in compressional foreland basins (e.g. Deramond et al., 1993; Willis, 1993 a,b; Horton and DeCelles; 1997; Morend et al., 2002; Cain and Mountney, 2009). Additionally, fluvial successions are also present in tectonically inactive basins, including slowly subsiding shelf edges and intracratonic basins (e.g. Harris et al., 1990; Bromley, 1991; Stephens, 1994). However, discerning the role that basin type plays in controlling the form of preserved sedimentary architecture in fluvial successions is not straightforward because typically several allogenic factors (e.g. climate, base level, nature of the sediment source) act in combination to influence sedimentary process and the resultant style of accumulation, as do autogenic processes related to the intrinsic behaviour of the type of fluvial system developing within the basin (e.g. Ventra and Nichols, 2014). Worldwide, relatively few regions are documented where the same geological formations represent the preserved deposits of the same fluvial system in multiple sedimentary basins of different type (Bromley, 1991; Wills, 2000). Studies from such regions provide the opportunity to compare lithotype and architectural-element proportion, distribution and arrangement within the general depositional environment of fluvial systems preserved in different tectonic settings.

This work investigates a Triassic fluvial succession of the Sherwood Sandstone Group in England, UK, present in two distinct sedimentary basins: the East Irish Sea Basin and the East England Shelf (Fig. 1). These two Triassic depocentres record the history of accumulation of fluvial successions in two tectonically different settings for which the style of preserved sediment fill is characterized by a range of fluvial channelized and non-channelized architectural elements, the arrangement of which is considered to have been influenced by basin setting. The East Irish Sea Basin represents a rift basin bounded by Triassic faults that underwent a relatively high rate of tectonic subsidence during the Triassic (61 m/Myr) attaining a burial depth of 4000 m, even in marginal areas such as West Cumbria at the end of the Cretaceous time (Chadwick et al., 1994; Akhurst et al., 1998). By contrast, the East England Shelf is a shelf-edge basin extending from the Pennines of Central England, eastwards across the East Midlands and Yorkshire towards the North Sea (Whittaker, 1985; Green, 1989; Bray et al., 1992). The amount of Triassic tectonic subsidence of the East England Shelf remains poorly constrained (Burley, 1984; Whittaker, 1985; Green, 1989; Bray et al., 1992). According to Burley (1984) the maximum burial depth of the East England Shelf is less than 1000 m before the Cenozoic uplift of Great Britain (*sensu* Chadwick, 1997; Blundell, 2002; Hills et al., 2008). The East England Shelf represents underwent a significantly slower rate of subsidence than the East Irish Sea Basin (Burley, 1984; Chadwick et al., 1994). Accommodation in the shelf-edge basin of the East England Shelf was governed by the presence of a palaeotopography formed by the adjacent Pennine highlands to the east, such that the preserved thickness of the Sherwood Sandstone Group progressively reduces eastward as it onlaps onto a palaeo-morphological high (Bath et al., 1987; Edmunds and Smedley, 2000; Smedley and Edmunds, 2002). Thus, the East England Shelf was not affected by tectonic extension and accommodation was generated by sediment loading and salt withdrawal of underlying evaporite deposits of the Permian Zechstein Group (Steward and Clark, 1997; Ruffel and Shelton, 1999; Noy et al., 2012, Banham and Mountney, 2013).

Although several previous studies provide useful overviews of the sedimentary structures that characterize fluvial (and aeolian and lacustrine) successions of the Sherwood Sandstone Group in the East Irish Sea Basin (e.g. Macchi, 1991; Jones and Ambrose, 1997, Nirex, 1997), no detailed lithofacies and architectural-element analysis has been published previously for the parts of the succession studied here. On the East England Shelf, no previous specific sedimentological work has been previously published from the study area and the sedimentary architecture of the Sherwood Sandstone Group deposits in this region is currently poorly constrained.

The aim of this study is to demonstrate the influence of basin type in governing the type and mechanism of preservation of a fluvial succession that accumulated and became preserved under conditions of active extensional tectonics and passive subsidence. Specific research objectives are as follows: (i) to undertake a lithofacies analysis of the fluvial successions present in two basins; (ii) to characterize and compare the form and geometry of channelized and non-channelized fluvial architectural elements present in two basins; (iii) to analyse palaeoflow indicators to demonstrate both the mechanism of bar-form growth and migration, and to reconstruct the regional pattern of palaeodrainage for two basins; (iv) to develop a sedimentary process model to show how the preserved sedimentary architectures of the studied fluvial successions are controlled by the different tectonic settings of the East Irish Sea Basin and the East England Shelf; (v) to present a conceptual model for braided-river systems, deposited in different tectonic settings but otherwise moderated by a common set of controlling allogenic factors; such a model can be applied to other rift settings where basins subject to relatively high rates of subsidence coexist with slowly subsiding basins.

2. Geological setting

The Sherwood Sandstone Group (Wuchiapingian-Ladinian) comprises a succession of red-beds accumulated in a series of basins developed in response to the rifting phase that preceded the opening of the Atlantic Ocean (Coward, 1995; Glennie, 1995; Ziegler and Dèzes, 2006). The “Sherwood Sandstone” has long been ascribed to a mixed fluvial and aeolian origin (e.g. Thompson, 1970 a, b; Cowan, 1993, Thompson and Meadows, 1997; Mountney and Thompson; 2002; Holliday et al., 2008). Collectively, the assemblage of lithofacies present in the succession demonstrates accumulation under the influence of an arid to semi-arid climatic regime, which characterized the UK Mesozoic basins during much of the Triassic (Warrington and Ivimey-Cook 1992; Glennie, 1995; Schmid et al., 2006; Brookfield, 2008). In the UK and Norwegian sectors of the North Sea Basin and in the East Irish Sea Basin, the Sherwood Sandstone Group forms an important reservoir for hydrocarbons (Meadows and Beach, 1993a,b; Mckinley et al., 2001; Schmid et al., 2004).

Additionally, the succession represents a potentially important, large-scale subsurface CO_2 storage reservoir (e.g. Holloway and Savage, 1993; Kirk, 2006, Heinemann et al., 2012; Noy et al., 2012). The unit forms the second largest groundwater aquifer in UK (Binley et al., 2002; Smedley and Edmunds, 2002).

Mesozoic extensional tectonic events created several basins and elevated areas in NW Europe during the Triassic. The morpho-structural highs that developed served as a principal source of sediment for fluvial systems and their accumulations. The Armorican Massif (northern France) represented the main source area for sediments of the Sherwood Sandstone Group in the UK, including and in off-shore parts of the East Irish Sea Basin (Wills, 1956; Audley and Charles, 1970; McKie and Williams, 2009; McKie and Shannon, 2011). Extensional tectonics continued to affect the Triassic basins of England throughout the Jurassic and Cretaceous (Ameen, 1995; Chadwick and Evans; 1995; Chadwick, 1997; Plant et al., 1999). Latterly, during the Cenozoic, the Triassic basins were reactivated and inverted by the far-field effects of the Alpine orogeny (Chadwick et al., 1994; Chadwick, 1997; Blundell, 2002; Hills et al., 2008).

The East Irish Sea Basin, which extends onshore in West Cumbria (Fig.1), is a Triassic rift basin bounded at its eastern margin by normal faults that divide it from the Lake District morpho-structural high (Akhurst et al., 1998). Within this region, the Sherwood Sandstone Group attains a maximum preserved thickness of 1100 m (Jones and Ambrose, 1997) and is formally divided into three different formations: the St Bees, Calder and Ormskirk Sandstone formations (Barnes et al., 1994; Akhurst et al. 1997; Holliday et al., 2008). The St Bees Sandstone Formation, which is the focus of this study, is characterized by predominantly by fine- to medium-grained sandstone of fluvial origin that passes upwards into the aeolian-dominated succession of the overlying Calder Sandstone Formation (Meadows, 1993a; Jones and Ambrose, 1994; Holliday et al., 2008). The St Bees Sandstone Formation is divided into two members, each with distinct lithological characteristics: the North Head Member and the overlying “St Bees Sandstone Formation above the North Head Member” (*sensu* Nirex, 1997). For clarity in this work, this upper member is referred to as the "South Head Member’’ because it is well exposed in outcrop along the South Head cliff in West Cumbria. The two members are differentiated primarily based on the abundance of fine-grained muddy sandstone and mudstone layers (Nirex, 1997). The basal 35 metres of the lower North Head Member are arranged into an alternation of sheet-like sandstone elements and mudstone elements. This lower succession passes upwards into a succession dominated by sandy-channalized architectural elements (Macchi, 1990; Barnes et al., 1994; Jones and Ambrose, 1994; Nirex, 1997).

In East England, the Sherwood Sandstone Group is undivided (i.e. no formal subdivisions of formation of member status). In this region, deposits of the Sherwood Sandstone Group crop out east of the Pennines (Fig.1) along the East England Shelf and attain a preserved thickness up to 400 m, but thin as they onlap the Permo-Carboinferous substratum to the west (Aitkenhead et al., 2002; Smedley and Edmunds, 2002). No detailed lithofacies analysis or palaeoenvironmental reconstruction of the sedimentology of the Sherwood Sandstone Group on the East England Shelf has previously been published. Generally, however, the Sherwood Sandstone of the East England Shelf is mostly represented by fine- to medium-grained sandstone present in a range of channelized architectural elements of fluvial origin; various types of cross-bedding are common (Pokar et al., 2006; West and Truss, 2006).

3. Data and Methods

A series of nine outcrops from natural cliffs, active and disused quarries, and with orientations both parallel and perpendicular to palaeoflow were studied in both the East England Shelf and in the East Irish Sea Basin on-shore in West Cumbria (Fig. 1) to characterize the internal sedimentary architecture of fluvial deposits of the Sherwood Sandstone Group. Thirteen lithofacies are recognized on the basis of lithological characteristics recognizable in outcrop: colour, grain-size, sorting, composition of matrix. Lithofacies have been assigned to two facies associations representative of channelized and non-confined (extra-channel) fluvial deposition. Four representative sedimentary log sections have been measured in the St Bees area (West Cumbria) and three in South Yorkshire. Additionally, a series of photomontages and architectural panels depict the distribution, style and juxtaposition of architectural elements. Principal erosional bounding surfaces from 5th to 6th-order (*sensu* Miall, 1985, 2006) have been mapped on photomontages which portray 30,100 m^2 of stratigraphic succession. Additionally, principal erosional surfaces (from 1st to 4th order) have been mapped on 4 four highly detailed architectural-element panels that collectively portray 360 m^2 of stratigraphic succession and record the following information: (i) the distribution and association of lithofacies; (ii) the internal geometry of six types of fluvial architectural element; (iii) a hierarchy of scales of bounding surfaces that define architectural elements based on a modified version of the scheme of Miall (1985, 2006); (iv) the spatial and genetic relationships between confined and non-confined architectural elements.

Palaeocurrent analysis of data recorded primarily from dip azimuths of inclined forests of cross-bedded sets, though supplemented by measurement of the axis trend of trough cross-bedded sets, has been undertaken to determine the following information: (i) regional patterns of palaeodrainage; (ii) detailed trajectories of barform growth; (iii) potential regions of sediment provenance. Statistical analyses, including determination of vector mean and vector magnitude, were calculated using the Stereonet 9 software package (Allimandinger, 2012). In total, 96 and 136 palaeocurrent readings were recorded from the St Bees Sandstone Formation (West Cumbria) and the Sherwood Sandstone cropping out in Dunsville Quarry (South Yorkshire), respectively.

4. Architectural elements and facies

Fluvial deposits of the Sherwood Sandstone Group have been studied in the St Bees-Whitehaven area in West Cumbria and in the Doncaster area, South Yorkshire. In West Cumbria and South Yorkshire (Figs. 2 and 3), the fluvial deposits are composed predominantly of very fine- to medium-grained sandstone (Figs. 4 and 5). In total, thirteen representative lithofacies of fluvial origin are recognized (Fig. 4, Table 1) and associations of these facies comprise the internal character of six architectural elements (Fig. 6).

In the St Bees and Whitehaven area, eleven of thirteen lithofacies are recognized and these occur in two facies associations: (i) channelized fluvial deposition and (ii) non-confined fluvial deposition. Within these two facies associations, six architectural elements are recognized (Figs. 7-10). Channelized fluvial deposition is recorded by the occurrence of interbedded channel-fill elements (F3) and laterally and vertically amalgamated channel-fill elements (F4). Non-confined fluvial deposition is characterized in the St Bees Sandstone Formation by red mudstone elements (F1), sheet-like sandstone elements (F2) and overbank elements interbedded in amalgamated channels (F5), sheet-like sandstone elements interbedded with amalgamated channels (F6).

In the Dunsville Quarry (South Yorkshire), seven lithofacies are recognized in two facies associations: (i) channelized fluvial deposition and (ii) non-confined fluvial deposition. These two facies associations are respectively related to two architectural elements (Figs.

11-13): laterally and vertically amalgamated channel-fill elements (F4) and overbank elements interbedded in amalgamated channels (F5).

Red mudstone elements (F1)

Description. The basal 35 m of the North Head Member of the St Bees Sandstone Formation outcropping at Saltom Bay (Fig. 7A and Fig. 7B) is dominated by an alternation of red mudstone elements (F1) and sheet-like sandstones (F2). Red mudstone elements are characterized by two sedimentary lithofacies: claystone and siltstone beds (Fm) and siltstone and very fine sandstone with ripple forms (Frc). Claystone and siltstone beds (Fm) are 0.1 to 0.6 m thick and characterized by bed-parallel laminations (Figs. 5 and 8). Some parallel laminated beds rarely pass laterally into siltstone and very-fine sandstone interbeds, which preserve ripple forms.

Interpretation. Red mudstone elements (F1) occur regularly interbedded with sheet-like sandstone elements (F2) and these elements likely have a co-genetic origin. During the initial flow stage, flow velocity was high and only sand was deposited. Progressively, flow velocity waned to zero and the claystone and siltstone component was deposited from suspension to form the red mudstone elements (cf. Hampton and Horton, 2007; Banham and Mountney, 2014).

Sheet-like sandstone elements (F2)

Description. Sheet-like sandstone elements up to 0.4 m thick are composed internally of fine-grained sandstone beds (Fsh) (Fig. 8). The base and the top of the sheet-sandstone bodies are generally sharp and the basal contact which divide F2 element from F1 is erosive. Additionally, there is a notable absence of upward fining within individual beds. The lateral continuity of sheet-like sandstone and red mudstone elements exceed the outcrop scale, which is 200 m along the Saltom Bay Cliff (Fig. 7A). On the basis of analysis of vertical stacking patterns, the sheet-like sandstone elements are more common and more amalgamated towards the top of the lower North Head Member. The stratigraphic succession exposed at Saltom Bay (Fig.7) demonstrates how the amount of amalgamation of sheet-like sandstone elements progressively increases higher in the stratigraphic succession of the lower North Head Member. Furthermore, the amount of amalgamation of sheet-like sandstone elements also increases upwards directly below channel elements that occur interbedded in the floodplain succession (Figs. 7B and 8).

Interpretation. Sheet-like sandstone elements represent the expression of repeated non-confined fluvial flood events (cf. Fisher et al. 2008). Sheet-like sandstone elements are co-genetic with red-mudstone elements and record deposition and accumulation during the initial part of a flood event. During the initial part of the flow event the energy was high and capable of erosion, as demonstrated by a sharp and erosional contact at the base of F2 elements. During the initial flow stage, the flow velocity was higher and only sand was deposited. In the aftermath of a flood, flow velocity progressively waned to zero and the claystone-siltstone component was deposited from suspension to form the red mudstone elements (F1).

The source of the sediment for accumulation of the sheet-like sandstone elements was likely crevasse-splay bodies, which introduced sand, silt and clay onto the alluvial plain during flood events (O'Brien and Wells, 1986; Smith, 1993; Bridge, 2003).

Interbedded channel-fill elements (F3)

Description. *C*hannel-fill elements occur interbedded within and encased by red mudstone (F1) and sheet-like sandstone (F2) elements in the lower North Head Member cropping out at Saltom Bay (Figs 7 and 8). Such interbedded channel-fill elements are delimited at their base by 4^{th} or 5^{th}-order bounding surfaces (*sensu* Miall, 1985, 2006). For example, along the Saltom Bay Cliff (Fig. 7), minor channel-fill elements are bounded by concave-upward erosive surfaces that are typical of 4^{th}-order bounding surfaces, whereas larger channel-fill elements interbedded with floodplain elements at Saltom Bay and North Head are bounded at their base by mostly flat, rarely concave-upward and laterally continuous erosive surfaces, which represent 5^{th}-order bounding surfaces.

The lowermost channel body exposed at Saltom Bay is 3 m thick and extends laterally for 50 m in sections perpendicular to palaeoflow. Laterally, the same stratigraphic section outcropping at Saltom Bay (Fig. 7) is characterized also by a fluvial interbedded (F3) and amalgamated channelized body (F4), which is 5 m thick and extends for at least 200 m, exceeding the outcrop extent. The internal lithofacies composition of F3 architectural elements is well exposed in a disused quarry (Hutbank Quarry) where a multi-storey channel body crops out (Fig. 8), the internal facies arrangement is of which comprises vertically stacked sets of compound cross-bedded units (Fx, Fxs, Fxt), which are each-up to 1 m thick. Multiple 3^{rd}-order bounding surfaces characterize the multi-storey channel-fill and these are delineated from the basal 4^{th}-order bounding surface (Fig. 8) in that the former downlap the basal erosive surface at angles up to 25°. Additionally, multiple 3rd-order bounding surfaces cut sets of cross-beds at low angles (usually < 15°) and are directly overlain by conglomerate lags comprising both intraclasts and dark igneous extraclasts (Fci, Fce), comprising 5% and 10% of the deposit, respectively.

Interpretation. Channel-fill elements (F3) occur interbedded with floodplain elements (F1 and F2) in the lower North Head Member of the St Bees Sandstone Formation. F3 architectural elements represent sediment bodies formed by stacked-fluvial bars, themselves formed from compound cross-bedded units (Fx, Fxs, Fxt). Overall, the main cliff section at Saltom Bay and Hutbank Quarry (Figs. 5, 8) reveals how the degree of amalgamation of sheet-like elements (Fig. 7B), which were fed by crevasse splays, increases higher in the stratigraphic succession below the erosive contact with the channel-fill elements (F3) interbedded in floodplain deposits. This systematic passage between amalgamated sheet-like sandstone elements (F2) and channelized elements(F3) shows the transition between distal crevasse splay deposits (sheet-like sandstone) and crevasse channels interbedded in the alluvial plain (cf. Banham and Mountney, 2014). A process of progradation of the fluvial system over time may explain the stacking of crevasse channels above sheet-like sandstones (Jones and Ambrose, 1994). Alternatively, processes of channel avulsion, possibly driven by activity on basin-margin faults, may explain the systematic transition between sheet-like sandstones fed by crevasse-splays into crevasse channels (cf. Leeder and Garthorpe, 1987; Brayant et al., 1995; Stouthamer and Berendsen, 2001; Aslan et al., 2005). Indeed, given that normal faults of half grabens generate increased accommodation towards the bounding extensional fault, deposits related to avulsions of crevasse channels tend to become preferentially stacked in locations close to the bounding tectonic structures (Leeder and Gawthorpe, 1987).

The presence of black igneous extraclasts in the fill of the crevasse-channels indicates a source from the Ordovician Borrowdale Volcanic Group (Strong et al., 1994), which has previously been interpreted to form part of the Lake District structural high (Jones and Ambrose, 1994).

Laterally and vertically amalgamated channel-fill elements (F4)

Description. Amalgamated channel-fill elements form 70% of the upper part of the North Head Member (Figs. 9 and 10) of the West Cumbrian St Bees Sandstone Formation. The degree of amalgamation of F4 elements increases higher in the stratigraphy and in the

South Head Member these elements represent the 95% of the stratigraphic record. In the North Head Member channels are separated by units of mudstone (Fig. 7C, F5) that are each up to 1 m thick, whereas in the South Head Member F4 elements are more amalgamated and F5 overbank elements are only rarely preserved.

Extraclasts of igneous origin comprise <2% of F4 elements in the St Bees Sandstone Formation, compared to 10% in the conglomerate lags of F3 channalized elements interbedded with floodplain deposits. Furthermore, igneous extraclasts are rare in F4 elements in the lower part of the South Head Member and are absent completely in the upper part.

Laterally and vertically amalgamated channel-fill elements (F4) are characterized in both West Cumbria and South Yorkshire by stacked barform deposits that comprise the fill of individual channel bodies (Figs. 9-13). The major bar structures comprise medium- to well-sorted, compound cross-bedded sets (Fx, Fxs, Fxt, Fxpb, Fxps) and horizontally planar sandstone (Fh) characterized by current lineations. Facies successions of different types of predominantly cross-bedded sets are characterized by an upward grain-size coarsening and decreasing in textural maturity (Fx, Fxpb, Fxps, Fxs, Fxt), with most successions capped by horizontally laminated beds (Fh). Barform deposits of F4 elements are asymmetrical in cross-section (Figs. 10 and 11B) revealing 1st, 2nd, 3rd-order erosional bounding surfaces that dip towards the dominant palaeoflow direction. Additionally, 2nd and 3rd-order erosional bounding surfaces are commonly overlain by sets that preserve avalanche deposits on their downstream faces. Dune-scale bedforms that are superimposed upon barform deposits differ from major bar-structures in that the former are dominated by trough cross-bedding (Fxt). Indeed, trough cross-bed sets comprise 60% of preserved dune bedform deposits but only 15% of barform deposits, which are instead dominated by planar and sigmoidal cross-bed sets (Fx, Fxs, Fxpb, Fxpx; collectively 60%). Ripple forms (Frc) and planar and sigmoidal cross-beds (Fx, Fxs) characterize dune-scale bedforms, accounting for 10% and 20% of these bedforms, respectively. Ripple forms (Frc) are commonly preserved climbing in downstream directions (Fig. 4). Compound cosets of dune-scale strata form sand bodies up to 1.5 m thick with troughs that are <1 m wide (Fig.13). Dune-scale bedforms are asymmetrical in cross-section; 1st- and 2nd-order erosional bounding surfaces dip towards the palaeoflow direction (Fig. 14). Foresets of dune-scale bedforms are inclined at angles up to 30°, whereas set and coset 3rd- and 4th-order bounding surfaces are typically inclined at angles up to 20° and 10°, respectively.

Red silty mudstones (Fm) are commonly associated with amalgamated channel-fill elements (F4) and form thin, 0.05 to 0.1 m-thick beds that drape the surface of cross-bedded sandstone bodies and which lack evidence of an erosional contact (Figs. 9 and 11B).

Major bar forms are characterized by a low-spread of cross bed-foresets azimuths. Foreset azimuths from cross-bedded sandstone beds (Fx, Fxs, Fxt) measured in the North Head and South Head members show an average palaeo-bedform migration direction towards the NNW (mean vector = 333°; mean vector length = 0,90; n=96). Palaeocurrent data (Fig. 5B) recorded from barform structures of the North Head Member indicate a vector mean of 318°, whereas cross-beds of stacked barforms of the South Head Member indicate a vector mean of 338° (Fig. 5B). Cross-bed foreset azimuths measured from cross-bedded sandstones (Fx, Fxps) that form stacked barform deposits at Dunsville Quarry (Fig. 5B) record an average palaeocurrent direction towards the NNE (mean vector = 024°; mean vector length = 0, 94; n=136); cross-bed foreset mean azimuths are 027° (n=19) and 023° (n=117), respectively for facies Fx and Fxps (Fig. 5B).

Despite the various common sedimentological characteristics between the studied stratigraphic successions in Cumbria and South Yorkshire, units of very fine-grained bleached sandstones and siltstones (Fwb) characterize only the amalgamated channels of the St Bees Sandstone Formation. Horizontally-laminated medium grained sandstones (Fh) and cross-beds (Fx, Fxs, Fxt) commonly are draped by these fine-grained bleached sandstones and siltstones (Fwb). Rarely, horizontally laminated, medium-grained sandstones (Fh) pass laterally into white, fine-grained sandstones (Fwb). These fine grained bleached sandstones are up to 0.2 m thick and they have a lateral extent of 2 to 50 m both parallel and perpendicular with respect to the palaeoflow. Amalgamated channel-fill elements (F4) in West Cumbria are additionally characterized by soft-sediment deformation structures in horizontally laminated sandstones (Fh). Sedimentary laminae are deformed by water-escape structures that form harmonic folds, flames and sand volcanoes (Fd; Fig. 4).

Two sedimentary facies that are only present in F4 elements at Dunsville Quarry are cross-bedded pebbly sandstone (Fxp) and cross-bedded pebbly sandstone with sigmoids (Fxps). These facies comprise well sorted, medium-grained sandstone beds that are characterized by rounded pebbles of extra-clasts (20 to 40 mm in diameter) and mud intraclasts up to 0.3 m in diameter. Cross-bedded pebbly sandstone (Fxp) and cross-bedded pebbly sandstone with sigmoids (Fxps) represent the most abundant lithofacies at Dunsville Quarry, together representing 50% of amalgamated channel-fill elements (F4).

Interpretation. Laterally and vertically amalgamated channel-fill elements (F4) studied in the East Irish Sea Basin and in the East England Shelf are characterized by stacked barform deposits, with the major bar structures comprising compound sets of cross-bedding and horizontally laminated, planar sandstones characterized by primary current lineations. The preserved deposits of these fluvial bars record dominantly downstream accretion as demonstrated by the presence 2^{nd}- and 3^{rd}-order erosional bounding surfaces that dip towards the palaeoflow direction, with avalanche deposits also present on the downstream facing foresets (Miall, 1977; Macchi, 1990). Bar forms characterized by cross-beds (Fx, Fxpb, Fxps, Fxs, Fxt) and superimposed horizontally laminated deposits (Fh) (Fig. 10B) might represent subaqueous bar platforms formed by cross-bedded sets that fine upward within F4 elements into horizontally laminated supra-platform deposits that signify episodic emergence (Steel and Thompson, 1983). This explains the upward coarsening and decrease in textural maturity of both cross-beds (Fx, Fxpb, Fxps, Fxs, Fxt) and horizontally laminated beds (Fh) (Steel and Thompson, 1983). This superimposition of facies reflects the migration of bar heads and bar tails over the bar platform (Bluck 1971, 1976) and demonstrates bifurcation of flow around mid-channel longitudinal bars (cf. Haszeldine, 1983; Steel and Thompson, 1983). The occurrence of downstream accreting barform deposits characterized by a low spread of foreset cross-bed dip azimuths and the bifurcation of flow around mid-channel longitudinal bars are typical of braided-fluvial systems (Collison, 1986; Bridge 1985, 1993, 2006). Additionally, the dune-scale bedforms record downstream accretion since the 1^{st}- and 2^{nd}-order erosional bounding surfaces dip towards to the palaeoflow direction and ripples that climb in a downstream direction are present. Such dunes are commonly reported from sand-dominated braided-river systems (e.g. Bristow, 1988; Reesink and Bridge, 2009; Ghinassi, 2011). Additionally, the generally coarse-grained composition of sand deposits, the paucity of mudstone and the abundance of planar cross-bedding have long been recognized as characteristics of braided fluvial systems (Coleman, 1969, Bristow, 1988).

The growth direction of the sandy bar forms is directed towards the NNW and NNE in the St Bees area (Cumbria) and in the Dunsville Quarry (South Yorkshire), respectively. The internal facies arrangement of the bar elements is such that cross-bedded sets and cosets represent barforms deposited under conditions of lower flow regime (Harms and

Falnestock, 1960; Miall, 1977). Horizontally laminated, planar sandstone facies with current lineations represent barforms whose upper surfaces experienced conditions of upper flow regime (Collinson et al., 2006).

Dune-scale bedform deposits that are superimposed upon barform deposits represent trains of dunes that were at least 1.5 m high (based on preserved set thicknesses), and which had crestline sinuosities that were <1 m wide (each separated by 2nd -order erosive surfaces); these dunes moved over the fronts of the larger bars (cf. Miall, 2010; Rubin and Carter, 2006; Ashworth et al., 2011).

In both the studied localities, red mudstone (Fm) units drape upper bar-surface topography and such deposits record accumulation under conditions of very low energy that likely occurred during the latest stages of a depositional event within a fluvial channel when the finest components were deposited from ponds developed in bar-top hollows via suspension settling (Bridge, 2006). These red-silty drape deposits (Fm) are more abundant in the St Bees Sandstone Formation of West Cumbria that the deposits in South Yorkshire.

The white, very fine-grained bleached sandstones and siltstones (Fwb) that are present in F4 elements only in the St Bees Sandstone Formation apparently accumulated as drapes over bed forms during episodes of low-stage flow (Jones and Ambrose, 1994). These Fwb deposits are coarse-grained equivalents to the red-silty drape deposits (Fm) and consequently record deposition under slightly higher energy conditions.

Soft-sediment deformation structures present in F4 elements in the St Bees Sandstone Formation could have been generated in response to seismic activity that induced liquefaction triggered by earthquakes (cf. Mohindra and Bagati, 1996; Berra and Felletti, 2011; Blanc et al., 1998; Moretti, 2000; Santos et al., 2012; Üner et al., 2012). Alternatively, the intense soft-sediment deformation could be related to relatively high rates of basin subsidence and penecontemporaneous sediment accumulation whereby recently accumulated deposits subsided rapidly beneath the water table (cf. Anketell et al., 1970; Owen and Moretti, 2011).

The relative abundance of cross-bedded pebbly sandstones with pebbles of both intraclast and extraclast origin in South Yorkshire may be related to: (i) a higher energy braided fluvial system, (ii) lower rates of subsidence and accommodation generation, which facilitated the reworking of fine-grained deposits in the upper part of fluvial bars and preferential preservation of channel base (thalweg) deposits (Burley, 1984; Chadwick et al., 1994); (iii) a closer proximity of the depocentre to the sediment source area.

Red mudstone interbedded with amalgamated channels (F5)

Description. Red-mudstone interbedded with laterally and vertically amalgamated channel fill-elements (F5) is characterized by reddish claystone and siltstone (Fm) as F1 elements. Despite this lithological common feature, F5 elements differ from F1 elements in that the former occur preserved between laterally and vertically amalgamated channel-fill elements (F4) and are not regularly interbedded with sheet-like sandstone. In the Upper North Head and South Head members of the St Bees Sandstone Formation (Fig. 7C), F5 elements composed of red mudstone are up to 0.6 m thick, and comprise 18% of the succession. In the South Head Member, F5 overbank elements comprise 5% of the succession and are up to 0.3 m thick. Similar red mudstone (Fm) deposits interbedded with amalgamated channels (F5 elements) are also present in the studied successions in South Yorkshire. Here, red mudstone units are arranged into single beds-up to 0.4 m thick (Fig. 11C). In all observed instances, the lateral extent of the fine-grained overbank deposits exceeds the outcrop scale.

Interpretation. These red mudstone F5 elements represent sediment deposits accumulated in the aftermath of overbank flood events (Kumar et al., 1999; Newell et al., 1999; Stanistreet et al., 2002). Such flood events were characterized by relatively low energy and transport of very-fine grained material (Platt and Keller, 1992; Owens et al., 1999; Ghazi and Mountney, 2009). These overbank deposits record non-confined flow at times when fluvial discharge exceeded the bank-full capacity of the fluvial channels (Bridge, 2003, 2006; Cain and Mountney, 2009).

Sheet-like sandstone elements interbedded with amalgamated channels (F6)

Description. Rare, sheet-like sandstones (F6) occur preserved between amalgamated channel-fills (Fig. 9) in the upper North Head Member and in the South Head Member. Sheet-like sandstone elements interbedded in amalgamated channels (F6) are exclusively characterized, as sheet-like sandstone (F2) of the lower North Head Member, by fine-grained sandstone sheet-beds (Fsh). Despite this common lithological characteristic, F6 architectural elements differ from F2 elements since the former do not occur regularly interbedded with red-mudstone elements (F1).

Interpretation. Sheet-like sandstone elements interbedded with amalgamated channel-fill elements (F6), like F5 elements, represent sediment deposits accumulated in the aftermath of overbank flood events (Kumar et al., 1999; Newell et al., 1999; Stanistreet et al., 2002). Sheet-like sandstone (F6) bodies occur interbedded with channel-fills in cases where the velocity of the unconfined flow was higher with respect to the flow velocity that deposited red mudstone during unconfined discharge events (Hampton and Horton, 2007; Banham and Mountney, 2014).

5. Discussion

Lithofacies and architectural element analyses have revealed how fluvial deposits of the Sherwood Sandstone Group in the successions from both West Cumbria and South Yorkshire are dominated by fluvial bar structures. These stacked barforms appear asymmetrical in along-stream cross-sections (Figs. 10 and 11) with 1st, 2nd and 3rd-order erosive bounding surfaces dipping towards the palaeoflow direction. Furthermore, 2nd and 3rd-order bounding surfaces also show avalanche surfaces dipping towards the palaeoflow. Dune-scale mesoform deposits dominated by trough cross-bedding and ripple forms occur superimposed upon bar form deposits (Fig. 13). Dune-scale mesoforms, as bar forms, record downstream accretion since erosive bounding surfaces dip towards the palaeocurrent direction and superimposed ripple forms climb downstream (Collinson, 1986; Bristow, 1988; Bridge, 2006; Rubin and Colter, 2006). Therefore it can be shown that both scales of bedform evolved predominantly via downstream accretion. The presence of downstream-accreting bedforms characterized by a low-spread of foreset cross-dip azimuths is indicative of the bifurcation of flow around mid-channel longitudinal bars in a braided-fluvial system (Haszeldine, 1983; Steel and Thompson, 1983, Collison, 1986; Bridge 1985, 1993, 2006). Additionally, the generally coarse-grained composition, paucity of mudstone, and the abundance of planar cross-bedded sandstone have long been recognized as characteristics of braided-fluvial systems (Coleman, 1969, Bristow, 1988). All these sedimentological characteristics support the interpretation of a sandy braided river system for the studied fluvial successions in both the East-Irish Sea Basin and the East England Shelf (Figs. 14 and 15).

Palaeocurrent data from the St Bees Sandstone Formation in the St Bees-Whitehaven area record a palaeoflow direction directed towards the NNW (Figs. 5B and 14), which implies a palaeodrainage that was aligned parallel to the Triassic boundary faults of the

East Irish Sea Basin (Fig. 2B), an arrangement also interpreted more regionally from the easternmost sector of the East Irish Sea Basin (Jones and Ambrose, 1994; Nirex, 1997; McKie and Williams, 2009).

Palaeocurrent indicators from the East England Shelf succession record palaeodrainage directed toward the NNE which is consistent with the regional drainage pattern of Sherwood Sandstone Group deposits in eastern England (Figs. 5B and 15). The spread of palaeocurrent along the East England Shelf ranges from NE to NW yielding a general sense of transport for the braided fluvial system towards north or NNE (Edwards et al., 1967; Smith and Francis, 1967; Powell et al., 1992; Gaunt et al., 1992; Gaunt and Goodwin, 1994).

Regional palaeogeographic reconstructions of the Triassic rift systems of NW Europe (Mckie and Williams, 2009; McKie and Williams, 2011; Tyrrell et al., 2012), coupled with sediment provenance studies, demonstrate that the primary sediment source was the Armorican Massif for both studied braided-fluvial systems (Wills, 1956; Audley and Charles; 1970; Mickie and Williams, 2009; Tyrrell et al., 2012; Morton et al., 2013). The Welsh Massif located 200 km south of the East Irish Sea Basin represents a likely secondary source of sediment for the St Bees Sandstone Formation (McKie and Williams, 2009; Tyrrell et al., 2012) and the Lake District Massif also contributed sediment from 30 km to the west (Jones and Ambrose, 1994; Strong et al., 1994). The London-Brabant Massif located 200 km south of the East England Shelf represents a likely secondary source of sediment for the Sherwood Sandstone Group in South Yorkshire (Fig. 1). The regional distribution of palaeocurrent indicators and the clast provenance excludes the paleo-Pennine uplift as a significant sediment source; the palaeoflow is directed parallel to this Triassic palaeo-morphological high for both the studied fluvial systems (Fig. 1).

The Armorican Massif occupied a palaeogeographic position ~550 to 600 km south of the East Irish Sea Basin and East England Shelf (McKie and Williams, 2009; Mickie and Shannon, 2011). Thus, the two studied depocentres received sediment that had been carried via a major fluvial system for a similar distance from both its primary source (Armorican Massif) and from potential secondary sources (Welsh Massif, Lake District Massif for the East Irish Sea Basin and London-Brabant Massif for the East England Shelf).

Although the two braided fluvial successions accumulated in two tectonically different sedimentary basins (Jones and Ambrose, 1994; Steward and Clark, 1987; Nirex, 1997;

Akhurst et al., 1998), they both share many similarities: (i) they are characterized by the same general depositional environment (braided fluvial system); (ii) they both have the same primary sediment source (Wills, 1956; Audley and Charles; 1970; Mickie and Williams, 2009; Tyrrell et al., 2012; Morton et al., 2013); (iii) they both accumulated at the same time in basins that shared a common palaeolatitude (McKie and Williams, 2009; Mickie and Shannon, 2011). Consequently, several of the principal allogenic factors that controlled sedimentation process (climate, sediment source and delivery style) were the same.

The braided-fluvial deposits of the tectonically active East-Irish Sea Basin have an average preserved thickness of 475 m in West Cumbria, which accumulated in 5 Myr (Jones and Ambrose, 1994; Nirex, 1997), yielding a time-averaged accumulation rate of 95 m/Myr. By contrast, the average preserved thickness of the Triassic braided-fluvial deposits on the East England Shelf is 200 m, which accumulated in 18 Myr (Warrington, 1982), yielding time-averaged accumulation rate of 11 m/Myr, this slower rate having been controlled by the slow rate of accommodation generation in this shelf-edge basin. The thickness of the braided-fluvial deposits of the North England Shelf and East-Irish Sea Basin are strongly influenced by the regional tectonic background. Indeed, the preserved thickness of Triassic fluvial deposits of the East-Irish Sea Basin varies systematically between the hangingwall and footwall of Triassic boundary faults (Jones and Ambrose, 1994; Nirex, 1997). The thickness of the Triassic fluvial deposits in the East England Shelf is constant along the strike of the shelf-edge basin but decreases progressively towards the palaeo-morphological structural high of the Pennines (Bath et al., 1987, Edmunds and Smedley, 2000; Atkinhead et al., 2002; Smedley and Edmunds, 2002). The thickness reduction of the braided-river succession moving from the hanging wall to the footwall of Triassic faults (East-Irish Sea Basin) or moving towards a paleo-morphological structural high (East England Shelf) demonstrate that local variations of energy played a relatively minor role in determining the preserved sediment thickness with respect to tectonic background.

Although the fluvial deposits of West Cumbria and South Yorkshire are characterized by a similar degree of sand sorting suggesting a comparable local energy regime, the stratigraphic succession of South Yorkshire is characterized by a relative paucity of fine-medium sandstone beds and a near complete absence of mudstone facies that drape bar-form tops (Figs. 5A and 15B, C). Given that the two studied depocentres are characterized by a common set of controls (e.g. climate, nature of primary sediment source, distance form secondary sediment sources, delivery style), and taking into account that they were governed by a similar local energy regime, differences related to the relative abundance of pebbly deposits verus fine-grained sandstone and mudstone deposits is most likely a function of the different tectonic background. In the East England Shelf succession, the vertical stacking of pebbly units and the general absence of fine-grained units reflects the slow rate of accommodation generation. In this shelf-edge basin, successive fluvial cycles repeatedly reworked the uppermost parts of earlier fluvial deposits such that only the basal-most channel lags tend to be preserved, whereas the finer-grained uppermost parts of fluvial cycles tend to be reworked. By contrast, in the East Irish Sea Basin of West Cumbria, the rate of accommodation generation was substantially greater such that space was available to preserve more complete fluvial cycles (Figs. 14B and C), including the finer-grained overbank units that cap the channelized deposits (Fig. 5A).

Another important difference between the studied fluvial successions is the presence of intense soft-sediment deformation only in West Cumbrian St Bees Sandstone Formation, the occurrence of which may be related to the tectonic realm in which the braided fluvial successions accumulated. Development of intense soft-sediment deformation may be related to movement on basin-bounding faults that resulted in seismic activity or to rapid rates of subsidence such that the accumulating succession rapidly subsided beneath the local water table, thereby rendering the deposits prone to liquefaction and de-watering in response to either seismic shaking or sediment loading (Anketell et al., 1970; Mohindra and Bagati, 1996; Blanc et al., 1998; Moretti, 2000; Owen and Moretti, 2011; Owen et al., 2011; Santos et al., 2012; Üner et al., 2012).

The sedimentary geology of the Sherwood Sandstone outcropping in the St Bees area is characterized by considerable geological complexity in terms of the style of vertical stacking of architectural elements, the variation in recorded palaeocurrent direction, and the variability in lithoclast types and proportions both spatially and especially temporally. This geological complexity at least partly reflects accumulation in a tectonically active basin that progressively evolved during the deposition of the Triassic braided-fluvial system that forms part of its infill (Jones and Ambrose, 1994; Ameen, 1995; Nirex, 1997; Akhurst et al., 1998). Preserved fluvial deposits in this basin record a clockwise 20° shift in palaeocurrent direction passing from the North Head Member to the South Head Member (Fig. 5B) that is associated with a progressive up-succession reduction in the frequency of occurrence of igneous extraclasts (derived from the Lake District Massif that lay to the east) above the lower North Head Member (Jones and Ambrose, 1994; Nirex, 1997), and their scarcity in the South Head Member. The variation in palaeocurrent direction and the reduction in the occurrence of extraclasts suggest a change in sediment supply from a system fed both from the south and from the Lake District Massif to the east, to a system fed almost entirely from a distant southerly source (the Armorican Massif).

In the early stages of their development, rift basins tend to be characterized by multiple, relatively small segmented basins occupied by interbedded channelized and floodplain elements (Gawthorpe and Leeder, 2000), similar to the preserved sedimentary expression of the lower North Head Member. In the early stages of the evolution of such rift basins, sediment supply tends to be derived from both local and distant sources. Over time, continued linkage of adjacent fault segments favours the development of elongated half-grabens (Ackermann et al., 2001; Mcleod et al., 2002) through which major rivers fed principally from distant sources pass (cf. Santos et al., 2014). Fault linkage prevents minor rivers from passing over the uplifted footwall blocks. The progressive disappearance of Lake District (Triassic horst) igneous extraclasts higher in the stratigraphy of the St Bees Sandstone may be explained by this style of evolution of the half-graben (cf. Gawthorpe and Leeder, 2000).

The progressive development of an elongated half-graben might also explain the 20° easterly shift of palaeocurrent between the North Head Member and the overlying South Head Member. During the deposition of the North Head Member, the main palaeoflow direction was partially directed towards the centre of the developing basin. Later, continued linkage favoured the development of a river pathway parallel and adjacent to the bounding faults, as recorded by palaeoflow indicators in the South Head Member (Fig. 5B). The preferential occurrence of floodplain deposits at the base of the St Bees Sandstone Formation has been assessed in detail in the Sellafield area, 20 km south of Saltom Bay (Gutmans et al., 1997; Nirex, 1997; Sterley et al., 2001). Interbedded channel-fill elements (F3) in this floodplain-dominated succession may represent the distal expression of the main channel belt, which at that time flowed in more southern parts of the basin (Jones and Ambrose, 1994). The basal part of the St Bees Sandstone Formation registers a systematic up-succession increase in the amalgamation of sheet-like sandstone elements to a level directly beneath the interbedded channel-fills (F3). Furthermore, this up-succession increase in the amalgamation of sheet-like sandstone elements in the North Head Member also characterizes the stratigraphy beneath the base of the succession dominated by laterally and vertically amalgamated channel-fill elements (F4). This superimposition of crevasse channels (F3) and laterally and vertically amalgamated channel-fill elements (F4) onto amalgamated sheet-like sandstones (F2) may be explained through the progradation of the braided-fluvial system northwards (Jones and Ambrose, 1994). The progressive northwards advancement of channalized architectural elements (F3, F4) could have created the superimposition of these channalized bodies onto sheet-like sandstones of crevasse-splays which represent the distal expression of both interbedded (F3) and amalgamated (F4) channel-fills.

Another process that could explain the increase in the amalgamation of sheet-like sandstone elements (F2) beneath crevasse channels (F3) is avulsion driven by fault activity typical of half-grabens modelled by Leeder and Gawthorpe (1987). Given that normal faults of half-grabens generate increased accommodation towards the bounding extensional fault, increased avulsion of crevasse channels would be expected closer to bounding tectonic structures (Bridge and Leeder, 1979; Leeder and Gawthorpe, 1987; Doglioni et al., 1998). Consequently, interbedded channels are predicted to progressively shift over time towards the bounding normal faults where they become stacked onto the lateral expression of the crevasse channels represented by amalgamated sheet-like sandstones (O'Brien and Wells, 1986; Smith, 1993; Bridge, 2003).

6. Conclusions

The fluvial systems of the St Bees Sandstone Formation of the East Irish Sea Basin and the undivided Sherwood Sandstone Group of the East England Shelf are both dominated by downstream-accreting sand-prone macroforms (bar deposits) that record evidence for the superimposed development of mesoforms indicative of the development of sinuous-crested dunes upon mid-channel bars. Despite the presence of many common depositional features between the two braided-river successions, three key differences relating to the style of preserved sedimentary architecture are identified: (i) differences in the thickness of the sediment preserved by erosion between a shelf-edge and a half-graben basin, (ii) the presence of thick pebble-beds characterized by compound cross-bedding only in the braided-fluvial deposits of the East England Shelf (shelf-edge basin), (iii) the relative paucity in the East England Shelf of either fine-grained deposits stacked between pebbly units or mudstones draping bar-tops.

The studied fluvial successions were affected by a similar set of allogenic factors, including climate, sediment source and sediment delivery style. However, a principal difference was the differential rates of accommodation generation at the time of sedimentation in response to differing tectonic subsidence between the two basins. Dividing the pre-existing average thickness values by the age of the fluvial deposits of the East-Irish Sea Basin and East England Shelf has allowed constraint of the preserved thickness sedimentation rates which were 95 and 11 m/Myr for the easternmost East Irish Sea Basin and the North East England Shelf, respectively. Basins subject to a faster rate of subsidence (e.g. East Irish Sea Basin) tend to be characterized by greater preserved thickness and by the preserved expression of more complete fluvial depositional cycles representative of channel cutting, filling by fine-grained sandy bar forms and abandonment as represented by silty drape bar-top deposits. However, in the East England Shelf, the vertical stacking of pebbly units and the general absence of fine-grained silty units reflects the slow rate of accommodation generation. In this shelf-edge basin, successive fluvial cycles repeatedly rework the uppermost parts of earlier fluvial deposits such that it is typically only the basalmost channel lags that are preserved, whereas the finest uppermost parts of the cycles are reworked.

An explicit outcome of this work is the development of a conceptual model for braided-river systems supplied from a common sediment source, and subject to similar climatic conditions, but deposited in different tectonic settings. This conceptual model may be applicable to other rift settings where basins subject to relatively high rates of subsidence coexist with slowly subsiding basins.

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Table captions

Tab.1: Summary of lithofacies observed in the Sherwood Sandstone Group of South East Yorkshire and West Cumbria (St Bees Sandstone Formation).

Tab.1: (continued)

Figure captions

Fig.1. Areas of study (red), UK Permo-Mesozoic sedimentary basins (grey) and potential feeder areas (white) for the Permo-Triassic clastic deposits outcropping in England.

Fig. 2. (A) Easternmost sector of the East Irish Sea Basin. (B) Geological map of the St Bees area in West Cumbria.

Fig. 3. (A) Geological map of the Dunsville area in South Yorkshire. (B) Detail of the Dunsville Quarry with location of the architectural panels

Fig. 4. Representative lithofacies of the Sherwood Sandstone Group in South East Yorkshire and West Cumbria. (A) Alternation red mudstone (Fm) and fine-grained sheet-sandstone (Fsh). (B) Planar cross-bedded sandstone; planar cross-beds. (C) Cross-

bedded sandstone with sigmoids; sigmoidal cross-beds and mud clasts. (D) Trough cross-bedded sandstone; laminae with erosive basal contact. (E) Horizontally laminated sandstone; bed parallel laminae. (F) Cross-bedded pebbly sandstone; planar cross-beds and mud clasts. (G) Cross-bedded pebbly sandstone with sigmoids; sigmoidal cross-beds and mud clasts. (H) Ripple laminated sandstone; climbing ripples. (I) White-fine grained siltstone/silty sandstone; thin beds of fine-grained sandstone draping coarser red sandstones. (J) Conglomerate/sandstone with extraformational clasts; dark extraclasts of igneous origin. (K) Conglomerate/sandstone with intraformational clasts. (L) Sandstone with deformed laminae; fine grained deposits deformed by a disharmonic fold (flames). (M) Sandstone with deformed laminae; sand volcano.

Fig.5 (A) Representative stratigraphic logs recorded in the Sherwood Sandstone Group fluvial deposits (South East Yorkshire, West Cumbria)in the locations in Figs. 2, 3. (B) Palaeocurrent data collected in the North Head Member and South Member and of the West Cumbrian St Bees Sandstone Formation and in the fluvial deposits of the Sherwood Sandstone Group in South Yorkshire.

Fig.6. Representative architectural elements, depicting generalized geometries and facies composition of the architectural elements characterizing the Sherwood Sandstone Group fluvial deposits (South East Yorkshire, West Cumbria).

Fig.7. Basal part of the St Bees Sandstone Formation. (A) North Head Member outcropping at Saltom Bay. (B) North Head Member: Basal 35 m of the St Bees Sandstone Formation: ‘1’ detail of amalgamated channel sheet-like sandstone (F2); ‘2’ interbedded channel fill-element (F3). (C) North Head Member: detail of overbank elements interbedded in amalgamated channels (F5).

Fig.8. Lower North Head Member; '1' Alternation of red mudstone and '2' sheet-like sandstone elements with an interbedded channel-fill element outcropping in the upper part of the Hutbank Quarry.

Fig.9. Upper part of the North Head Member: '1' coarse sandstone of laterally and vertically amalgamated channel-fill complexes; '2' Red-silty drape mudstone part of amalgamated channel-fill complexes; '3' Sheet-like sandstone element interbedded in amalgamated channel-fill complexes.

Fig.10. Architectural panels showing the fluvial architecture of laterally and vertically amalgamated channel-fill elements in a section perpendicular to palaeoflow direction (South Head Member). (A) Downstream dipping of 2^{nd}, 3^{rd} erosive bounding surfaces with occasional avalanche faces. (B) Superimposition of bed-parallel beds (Fh) of bar platform onto cross-beds (Fx, Fxs) representing supra-platform deposits.

Fig.11. (A) Laterally and vertically amalgamated channels elements outcropping in Dunsville Quarry: downstream accretion of sandy bed-forms. (B) Laterally and vertically amalgamated channels elements outcropping in the Dunsville Quarry in view perpendicular respect to the palaeoflow: red-silty mudstone draping a sandy bar form. (C) Overbank element: '1' red silty mudstone related to unconfined flow; '2' channelized architectural elements at top and bottom of the overbank element.

Fig.12. Architectural panel showing the fluvial architecture of laterally and vertically amalgamated channel fill elements of the Sherwood Sandstone Group (Dunsville Quarry). View perpendicular to palaeoflow direction.

Fig.13. Architectural panel showing the architecture of dune scale bed-forms of laterally and vertically amalgamated channel-fill complexes of the Sherwood Sandstone Group (Dunsville Quarry) in a section oriented parallel to inferred palaeoflow.

Fig.14. Summary model of the vertical and lateral architecture of the Sherwood Sandstone Group braided deposits in the easternmost sector of the East-Irish Sea Basin. (A) Braided river system in the half-graben basin of the East Irish Sea Basin. (B) Depositional model of the St Bees Sandstone Formation of West Cumbria. (C) Cross-section of a typical braided bar characterizing the St Bees Sandstone Formation

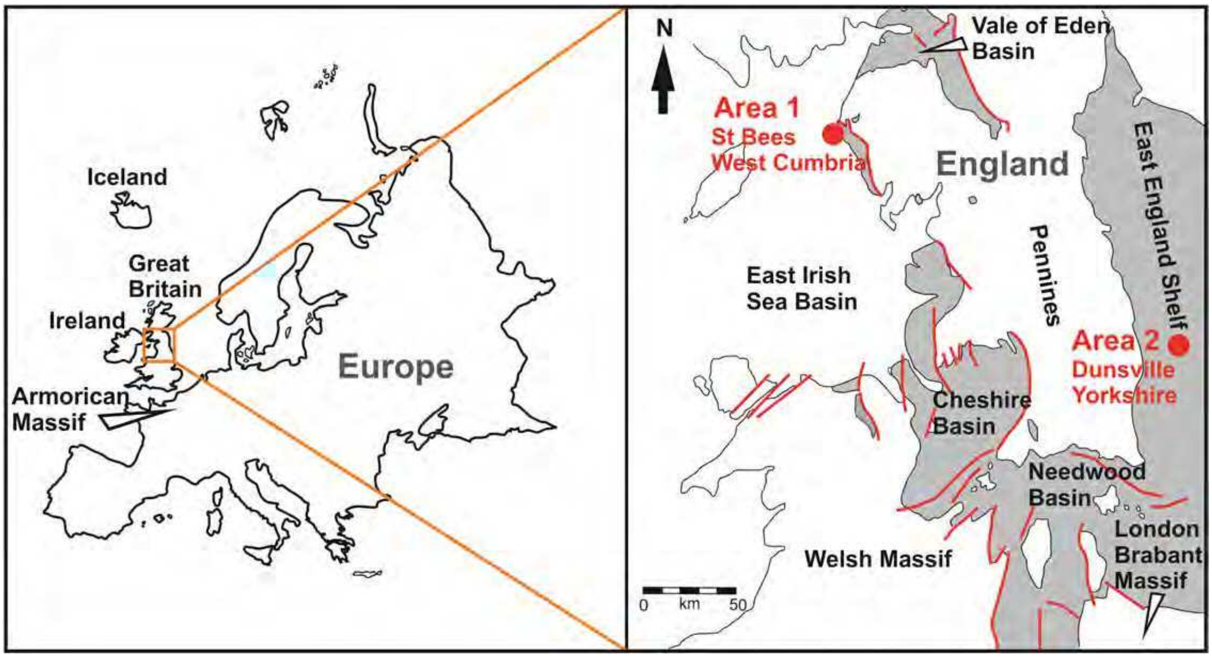
Fig.15. Summary model of the vertical and lateral architecture of the Sherwood Sandstone Group braided deposits of the East England Shelf. (A) Braided river system in shelf edge-basin (East Irish Sea Basin). (B) Depositional model of the Sherwood Sandstone Group of South Yorkshire. (C) Cross-section of a typical braided bar characterizing the Sherwood Sandstone Group of South Yorkshire.

Facies	Description	Interpretation
Red mudstone (Fm)	Mudstone that is red in colour and forms beds that are each 0.05-1m thick. The red mudstone is characterized by an alternation of clay- and silt-prone layers.	Thick and laterally continuous mudstone beds represent deposition from suspension during overbank events. Thin and laterally discontinuous mudstone beds record deposition from suspension in abandoned channels.
Fine grained sandstone (Fsh)	Very fine-grained sandstone that occurs in alternation with Fm to form beds that are up to 0.4 m thick. Alternatively, Fsh occurs in single layers (0.2-0.5 m thick) interbedded with medium and coarse sandstone beds. Fsh exhibits bed-parallel laminations.	Deposition during discharge events for which flow was not confined within channels. Records flow velocities that were greater than those indicated by facies Fm.
Planar cross-bedded sandstone (Fx)	Moderate- to well-sorted, fine- to medium-grained tabular sandstone arranged in beds that are 1-1.5 m thick. Fx exhibits planar cross-bedded foresets which rarely are bleached white. Cross-bedded foresets are inclined at angles of 25°-30° with respect to master set bounding surfaces.	Deposition of sandy bar forms under lower flow regime conditions, including down-channel migration of sinuous-crested dunes.
Cross-bedded sandstone preserving sigmoidal foreset shape (Fxs)	Moderately sorted, fine- to medium-grained tabular sandstone. Foresets are sigmoidal and show tangential contact with basal bounding surfaces.	Migration and deposition of sandy bar forms within a fluvial channel; dominantly records downstream accretion under lower flow regime conditions by the downstream migration of sinuous-crested dunes.
Trough cross-bedded sandstone (Fxt)	Fine- to medium-grained sandstone that most commonly occurs in packages of multiple sets of trough cross-bedding. The basal surfaces of sets are erosional. This facies is arranged into beds that are each 0.5-1 m thick. Cross strata pass laterally and upward within sets into planar-tabular cross-bedded sets.	Sandy bar forms within a fluvial channel; dominantly records downstream accretion under lower flow regime conditions by the downstream migration of sinuous-crested dunes.
Horizontally laminated sandstone (Fh)	Very well-sorted, fine-grained sandstone. Fh is characterized exclusively by bed-parallel laminations in the form of primary current lineations.	Migration and deposition of sandy bar forms under upper flow regime conditions.
Cross-bedded, Pebbly sandstone (Fxpb)	Well sorted, fine to medium grained, cross-bedded pebbly sandstone. Fxpb is abundant in quartz, feldspar and rounded pebble-grade extraclasts including black concretions of heavy minerals. Pebbles range in diameter from 20-40 mm. Black clasts are typically 10-20 mm in diameter. Fxpb is also abundant in yellow (30-40 mm) and red mud clasts (5-300 mm).	Migration and deposition of pebbly bar forms under lower flow regime conditions.

Tab.1: Summary of lithofacies observed in the Sherwood Sandstone Group of Cumbria (St Bees Sandstone Formation) and South Yorkshire.

Facies	Description	Interpretation
Cross-bedded pebbly sandstone with sigmoidal foreset shapes (Fxps)	Well-sorted, fine- to medium-grained sandstone with pebbles. Rounded quartz and feldspar pebbles, mud clasts and black concretions are common. Pebbles range from 20-40 mm in diameter as for facies Fxpb. Mud clasts are smaller than those in facies Fxpb: their diameter ranges from 20-60 mm. Black concretionary pebbles are 10-20 mm in diameter. Cross-bedding preserves sigmoidal foreset shapes. Low-angle inclined bottom-sets are present.	Migration and deposition of sandy bar forms within a fluvial channel; downstream accretion under conditions of lower flow regime.
White, fine-grained siltstone and silty sandstone (Fwb)	Mostly siltstone and subordinate fine-grained sandstone interbedded with cross-bedded and horizontally laminated sandstone. Fwb occurs as beds that are each 0.1-0.15 m thick, with a lateral continuity of 30-50 m; typically white in colour. Abundant desiccation cracks.	Drapes that overlie bedform deposits; records deposition during relatively low-energy flow conditions.
Ripple laminated sandstone (Frc)	Moderately sorted, fine-grained sandstone. Ripple strata typically climb at angles < 10°, but can climb up to 15°. Ripple forms are sinuous crested.	Represents down-channel migration, climb and accumulation of sinuous-crested ripples.
Sandstone with deformed laminations (Fd)	Fine-grained sandstone characterized by deformed, originally horizontal laminations; deformation expressed as harmonic and disharmonic folds with antiform shapes and sand volcanoes. Disharmonic folds (flames) exhibit sharp cut of the overlying sedimentary laminations.	Deformation due to sudden water escape with increasing pressure related to rapid burial or to instantaneous seismic shaking.
Conglomerate and sandstone with extraformational clasts (Fce)	Conglomerate and sandstone with angular to sub-angular, commonly dark-coloured clasts of igneous and metamorphic origin. Most commonly these clasts occur in the lowermost 50-100 mm of sets. Clasts are 50-150 mm in diameter.	Lag deposits, representing coarsest sediment fraction transported by the flow during high-energy conditions, likely in channel thalwegs. The angular nature of the clasts reflects a limited distance of transport and a local sediment source.
Conglomerate and sandstone with intraformational clasts (Fci)	Conglomerates and sandstone; fine-to coarse grained sand matrix with reddish mudstone clasts that are 10-40 mm in diameter. Clasts are sub-rounded to sub-angular.	Intraclasts record the localised reworking of mudstone beds (Fm), with clasts derived either via erosion from the base of the channel or from bank collapse at the channel margin.

Tab.1:(continued)


Iceland
Great Britain
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Europe
Armorican Massif
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Area 1
St Bees
West Cumbria
Vale of Eden Basin
England
East England Shelf
East Irish Sea Basin
Pennines
Area 2
Dunsville
Yorkshire
Cheshire Basin
Needwood Basin
London Brabant Massif
Welsh Massif
0 km 50

Fig.1

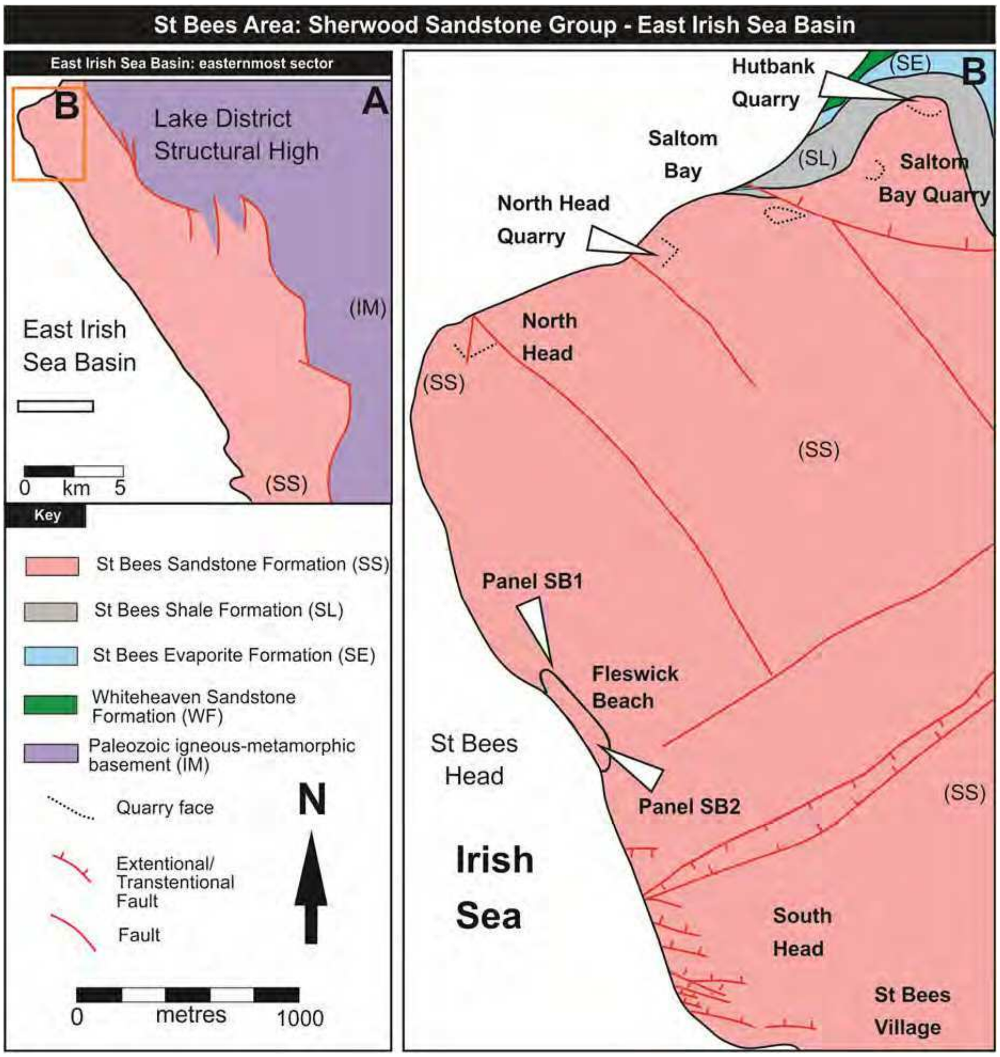

St Bees Area: Sherwood Sandstone Group - East Irish Sea Basin
East Irish Sea Basin: easternmost sector
A
B
Lake District
Structural High
(IM)
East Irish
Sea Basin
0 km 5
(SS)
Key
St Bees Sandstone Formation (SS)
St Bees Shale Formation (SL)
St Bees Evaporite Formation (SE)
Whiteheaven Sandstone Formation (WF)
Paleozoic igneous-metamorphic basement (IM)
Quarry face
Extentional/ Transtentional Fault
Fault
N
0 metres 1000
Hutbank Quarry
(SE)
Saltom Bay
(SL)
Saltom Bay Quarry
North Head Quarry
North Head
(SS)
Panel SB1
Fleswick Beach
St Bees Head
Panel SB2
Irish Sea
South Head
St Bees Village

Fig.2

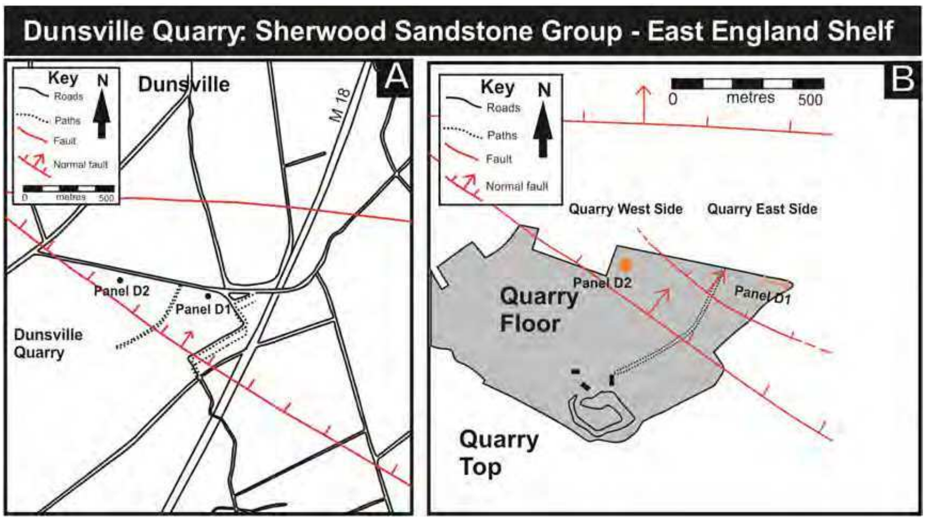

Dunsville Quarry: Sherwood Sandstone Group - East England Shelf
A
Key
N
Roads
Paths
Fault
Normal fault
metres 500
Dunsville
M 18
Panel D2
Panel D1
Dunsville Quarry
B
Key
N
Roads
Paths
Fault
Normal fault
0 metres 500
Quarry West Side
Quarry East Side
Panel D2
Panel D1
Quarry Floor
Quarry Top

Fig.3

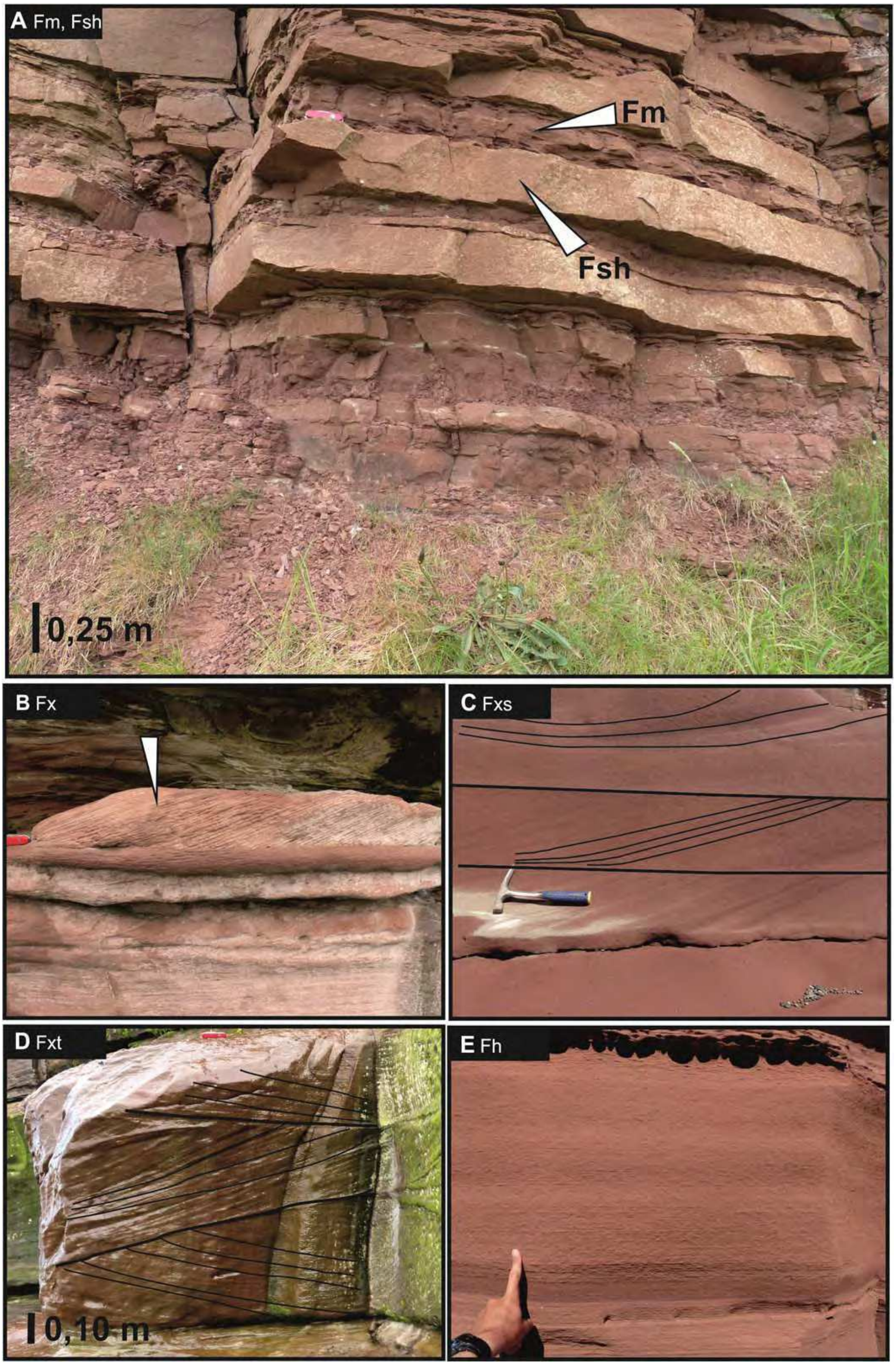
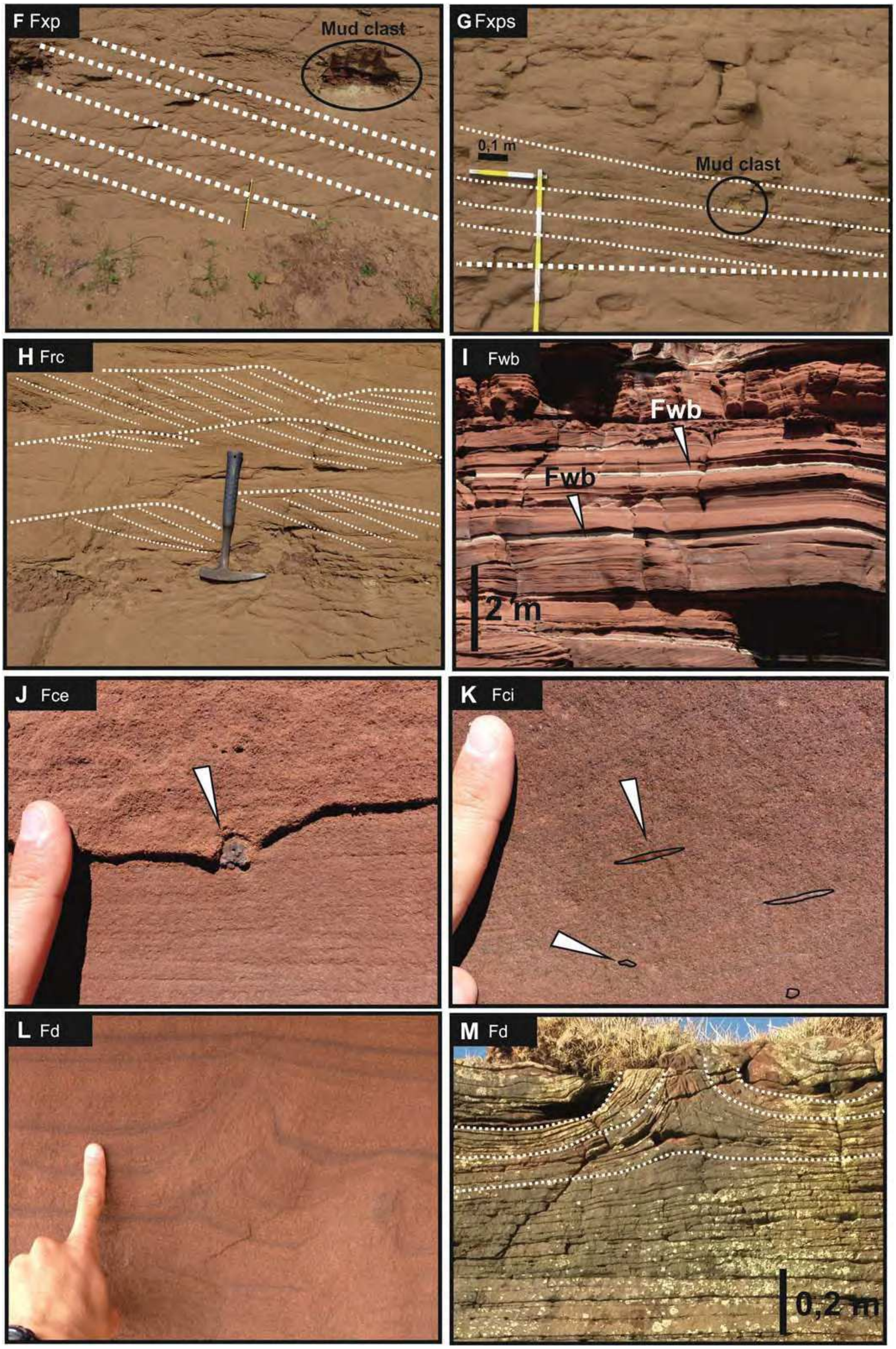


Fig.4



Fog.4 continued

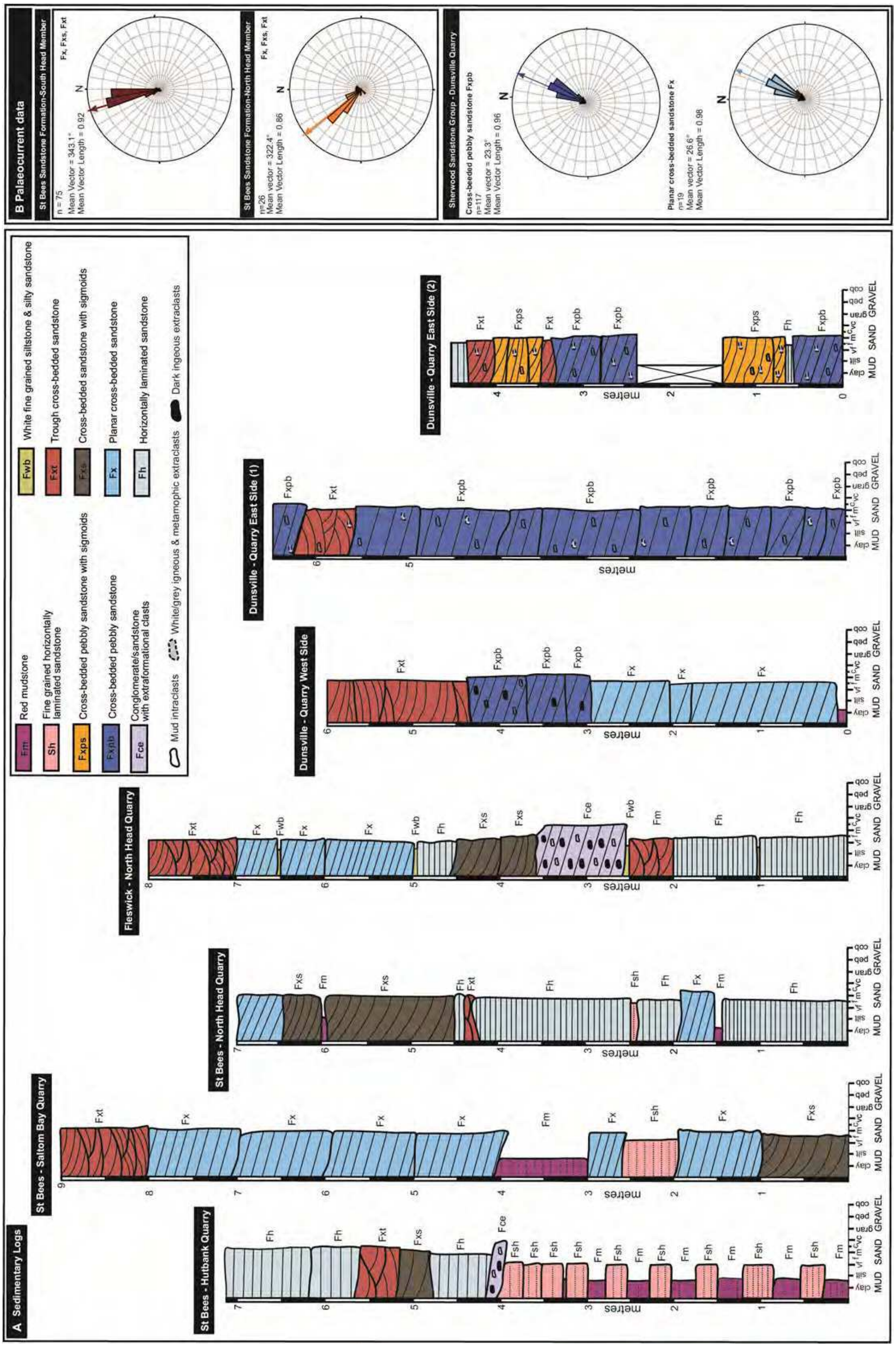
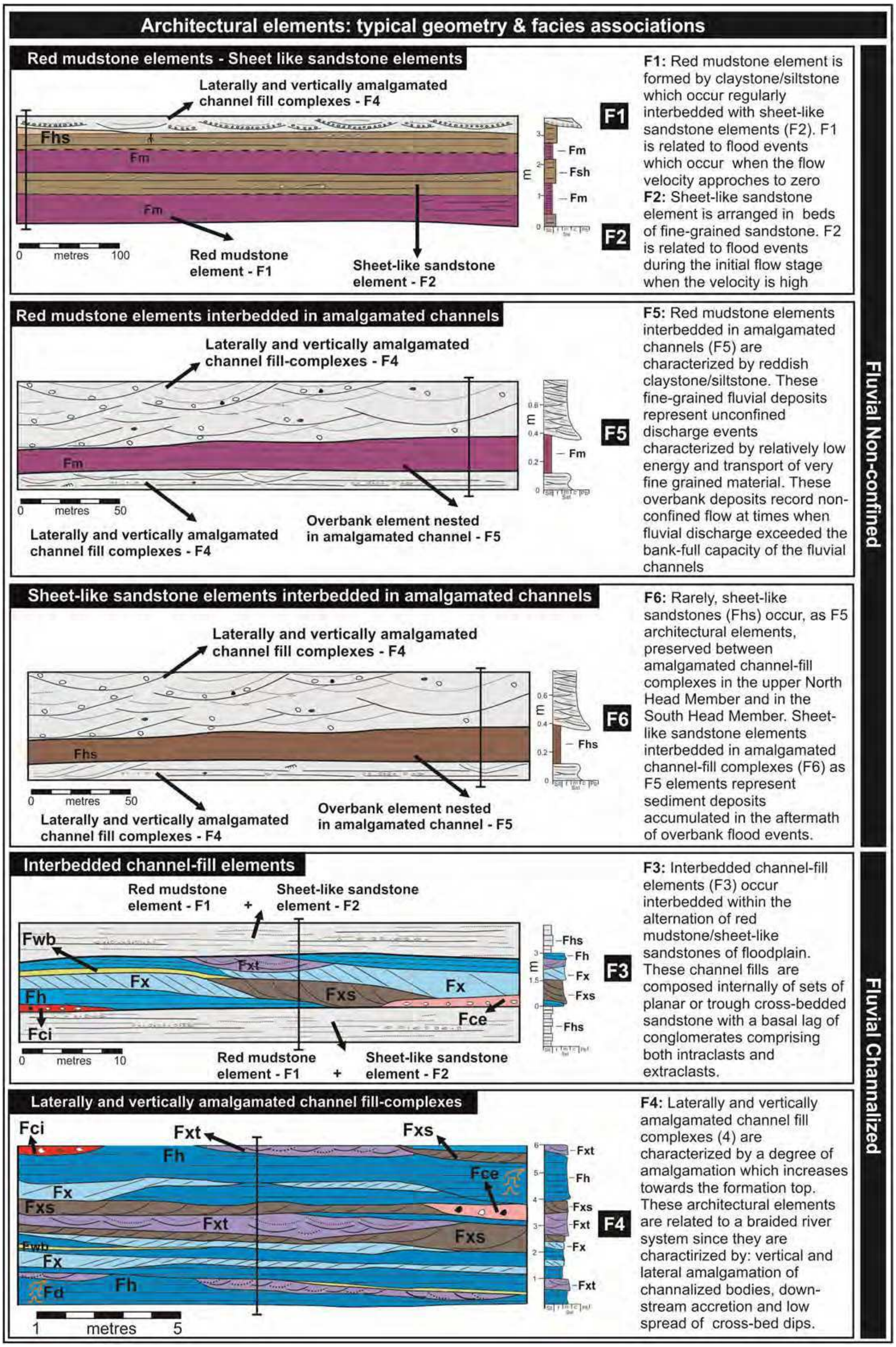

A Sedimentary Logs
St Bees - Hutbank Quarry
St Bees - Saltom Bay Quarry
St Bees - North Head Quarry
Fleswick - North Head Quarry
Dunsville - Quarry West Side
Dunsville - Quarry East Side (1)
Dunsville - Quarry East Side (2)
Fm Red mudstone
Sh Fine grained horizontally laminated sandstone
Fxps Cross-bedded pebbly sandstone with sigmoids
Fxpb Cross-bedded pebbly sandstone
Fce Conglomerate/sandstone with extraformational clasts
Fwb White fine grained siltstone & silty sandstone
Fxt Trough cross-bedded sandstone
Fxs Cross-bedded sandstone with sigmoids
Fx Planar cross-bedded sandstone
Fh Horizontally laminated sandstone
Mud intraclasts
White/grey igneous & metamorphic extraclasts
Dark ingeous extraclasts
metres
MUD SAND GRAVEL
B Palaeocurrent data
St Bees Sandstone Formation-South Head Member
n = 75
Mean Vector = 343.1°
Mean Vector Length = 0.92
Fx, Fxs, Fxt
St Bees Sandstone Formation-North Head Member
n=26
Mean vector = 322.4°
Mean Vector Length = 0.86
Fx, Fxs, Fxt
Sherwood Sandstone Group - Dunsville Quarry
Cross-beded pebbly sandstone Fxpb
n=117
Mean vector = 23.3°
Mean Vector Length = 0.96
Planar cross-bedded sandstone Fx
n=19
Mean vector = 26.6°
Mean Vector Length = 0.98

Fig.5



Architectural elements: typical geometry & facies associations
Red mudstone elements - Sheet like sandstone elements
Laterally and vertically amalgamated channel fill complexes - F4
Fhs
Fm
Fm
0 metres 100
Red mudstone element - F1
Sheet-like sandstone element - F2
m
Fm
Fsh
Fm
F1
F2
F1: Red mudstone element is formed by claystone/siltstone which occur regularly interbedded with sheet-like sandstone elements (F2). F1 is related to flood events which occur when the flow velocity approches to zero
F2: Sheet-like sandstone element is arranged in beds of fine-grained sandstone. F2 is related to flood events during the initial flow stage when the velocity is high
Red mudstone elements interbedded in amalgamated channels
Laterally and vertically amalgamated channel fill-complexes - F4
Fm
0 metres 50
Laterally and vertically amalgamated channel fill complexes - F4
Overbank element nested in amalgamated channel - F5
m
Fm
F5
F5: Red mudstone elements interbedded in amalgamated channels (F5) are characterized by reddish claystone/siltstone. These fine-grained fluvial deposits represent unconfined discharge events characterized by relatively low energy and transport of very fine grained material. These overbank deposits record non-confined flow at times when fluvial discharge exceeded the bank-full capacity of the fluvial channels
Sheet-like sandstone elements interbedded in amalgamated channels
Laterally and vertically amalgamated channel fill complexes - F4
Fhs
0 metres 50
Laterally and vertically amalgamated channel fill complexes - F4
Overbank element nested in amalgamated channel - F5
m
Fhs
F6
F6: Rarely, sheet-like sandstones (Fhs) occur, as F5 architectural elements, preserved between amalgamated channel-fill complexes in the upper North Head Member and in the South Head Member. Sheet-like sandstone elements interbedded in amalgamated channel-fill complexes (F6) as F5 elements represent sediment deposits accumulated in the aftermath of overbank flood events.
Fluvial Non-confined
Interbedded channel-fill elements
Red mudstone element - F1 + Sheet-like sandstone element - F2
Fwb
Fxt
Fx
Fh
Fxs
Fx
Fce
Fci
0 metres 10
Red mudstone element - F1 + Sheet-like sandstone element - F2
m
Fhs
Fh
Fx
Fxs
Fhs
F3
F3: Interbedded channel-fill elements (F3) occur interbedded within the alternation of red mudstone/sheet-like sandstones of floodplain. These channel fills are composed internally of sets of planar or trough cross-bedded sandstone with a basal lag of conglomerates comprising both intraclasts and extraclasts.
Laterally and vertically amalgamated channel fill-complexes
Fci
Fxt
Fxs
Fh
Fce
Fx
Fxs
Fxt
Fxs
Fwb
Fx
Fh
Fd
1 metres 5
Fxt
Fh
Fxs
Fxt
Fx
Fxt
F4
F4: Laterally and vertically amalgamated channel fill complexes (4) are characterized by a degree of amalgamation which increases towards the formation top. These architectural elements are related to a braided river system since they are charactirized by: vertical and lateral amalgamation of channalized bodies, down-stream accretion and low spread of cross-bed dips.
Fluvial Channalized

Fig.6

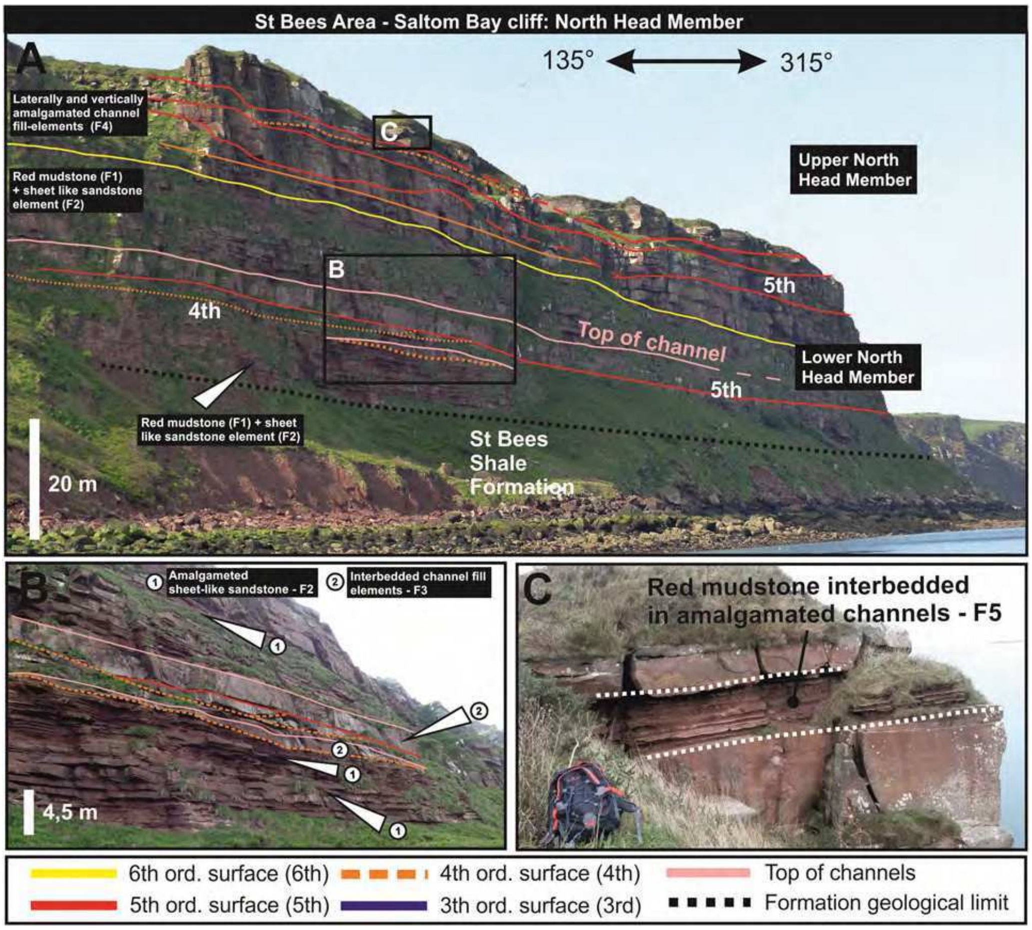

St Bees Area - Saltom Bay cliff: North Head Member
A
135° 315°
Laterally and vertically amalgamated channel fill-elements (F4)
C
Upper North Head Member
Red mudstone (F1) + sheet like sandstone element (F2)
B
5th
4th
Top of channel
Lower North Head Member
5th
Red mudstone (F1) + sheet like sandstone element (F2)
St Bees Shale Formation
20 m
B
1 Amalgameted sheet-like sandstone - F2
2 Interbedded channel fill elements - F3
4,5 m
C
Red mudstone interbedded in amalgamated channels - F5
6th ord. surface (6th)
4th ord. surface (4th)
Top of channels
5th ord. surface (5th)
3th ord. surface (3rd)
Formation geological limit

Fig.7

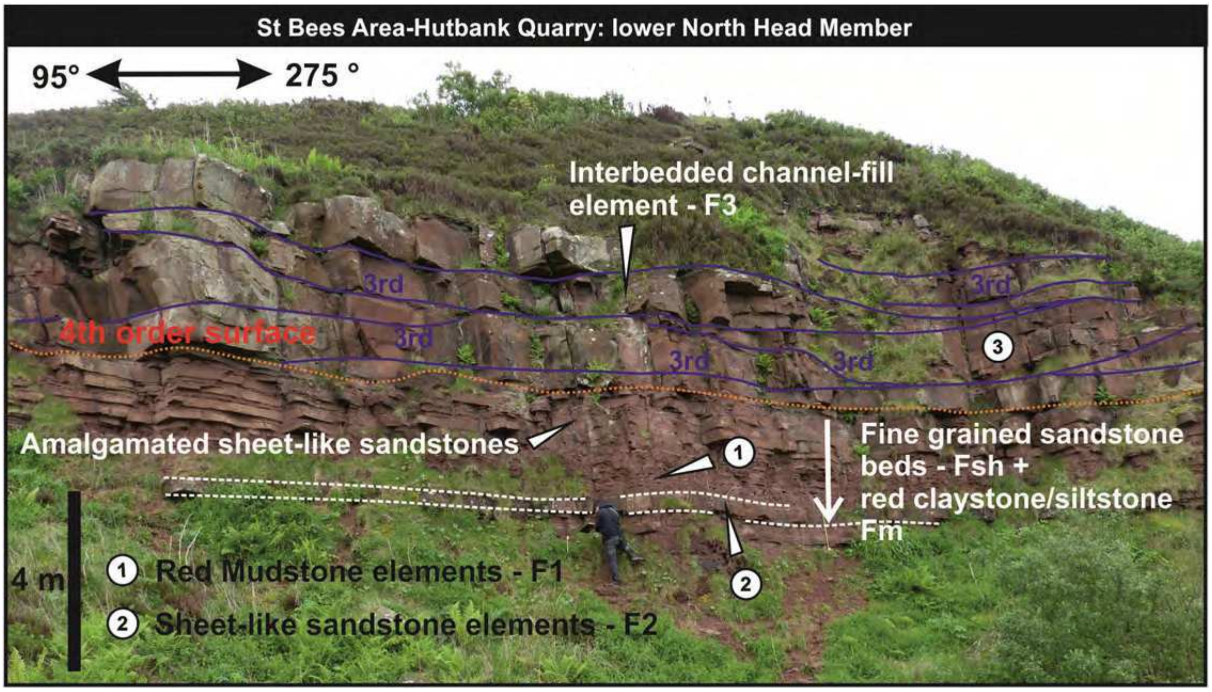

St Bees Area-Hutbank Quarry: lower North Head Member
95° 275 °
Interbedded channel-fill element - F3
3rd
4th order surface
3rd
3rd
3rd
3rd
3
Amalgamated sheet-like sandstones
1
Fine grained sandstone beds - Fsh + red claystone/siltstone Fm
4 m
1 Red Mudstone elements - F1
2
2 Sheet-like sandstone elements - F2

Fig.8

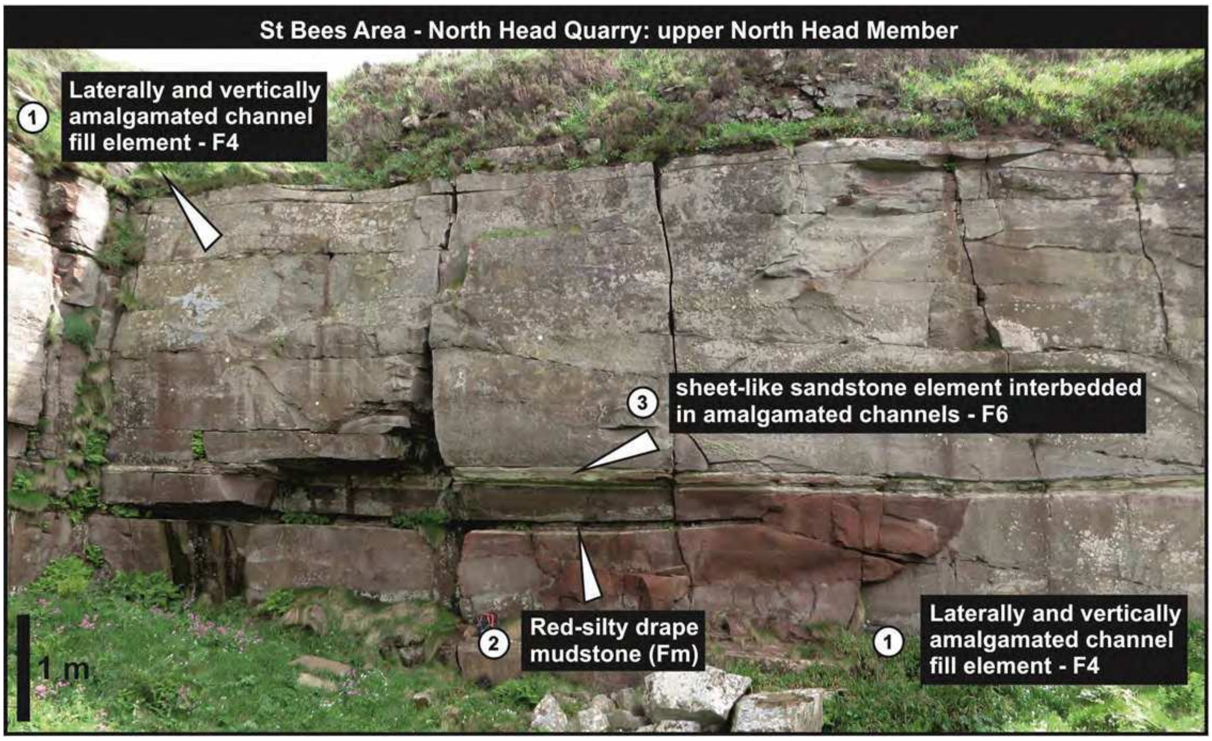

St Bees Area - North Head Quarry: upper North Head Member
1
Laterally and vertically amalgamated channel fill element - F4
3
sheet-like sandstone element interbedded in amalgamated channels - F6
2
Red-silty drape mudstone (Fm)
1
Laterally and vertically amalgamated channel fill element - F4
1 m

Fig.9

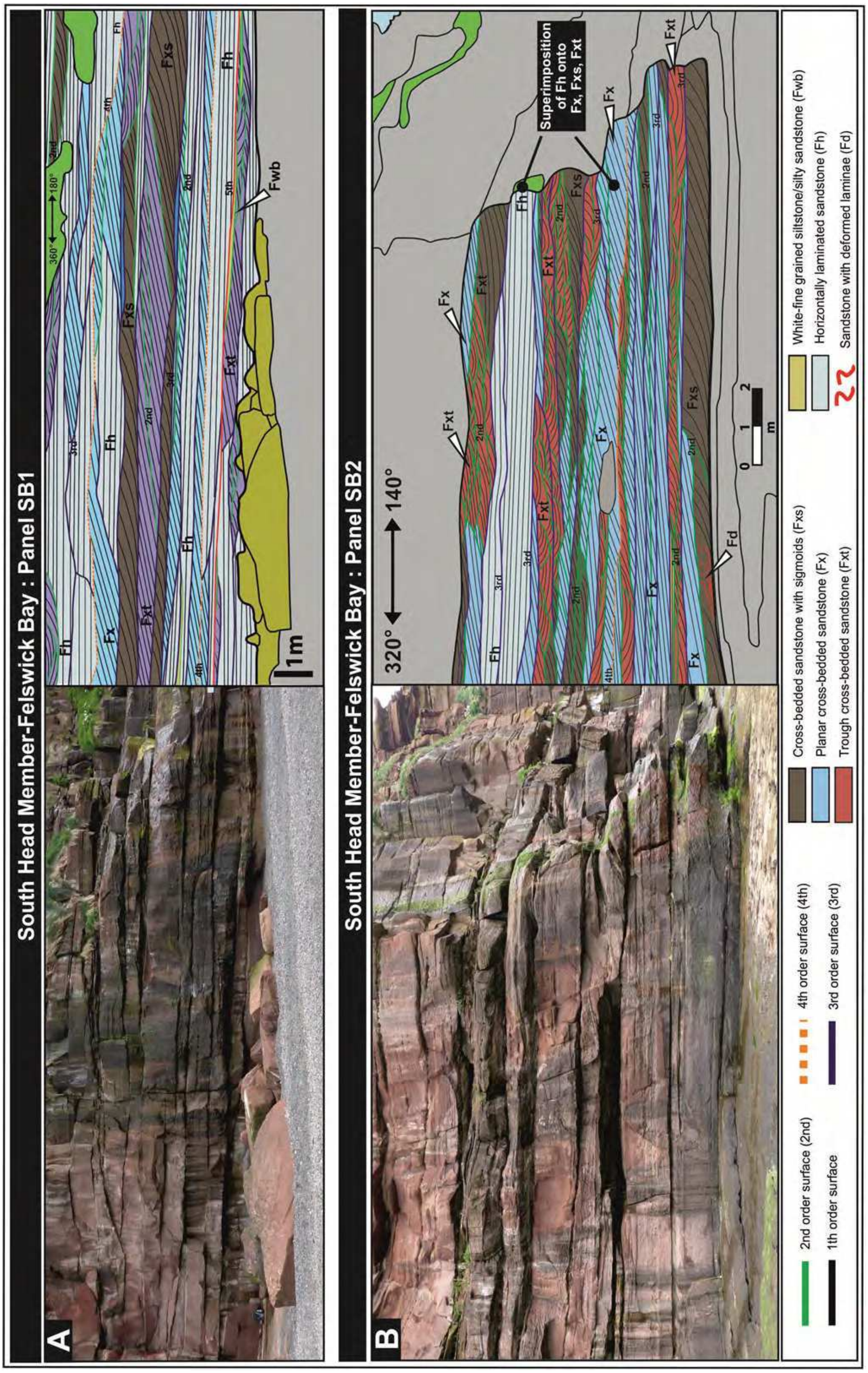

A
South Head Member-Felswick Bay : Panel SB1
B
South Head Member-Felswick Bay : Panel SB2
320°
140°
Superimposition of Fh onto Fx, Fxs, Fxt
1 m
2nd order surface (2nd)
1th order surface
4th order surface (4th)
3rd order surface (3rd)
Cross-bedded sandstone with sigmoids (Fxs)
Planar cross-bedded sandstone (Fx)
Trough cross-bedded sandstone (Fxt)
White-fine grained siltstone/silty sandstone (Fwb)
Horizontally laminated sandstone (Fh)
Sandstone with deformed laminae (Fd)

Fig.10

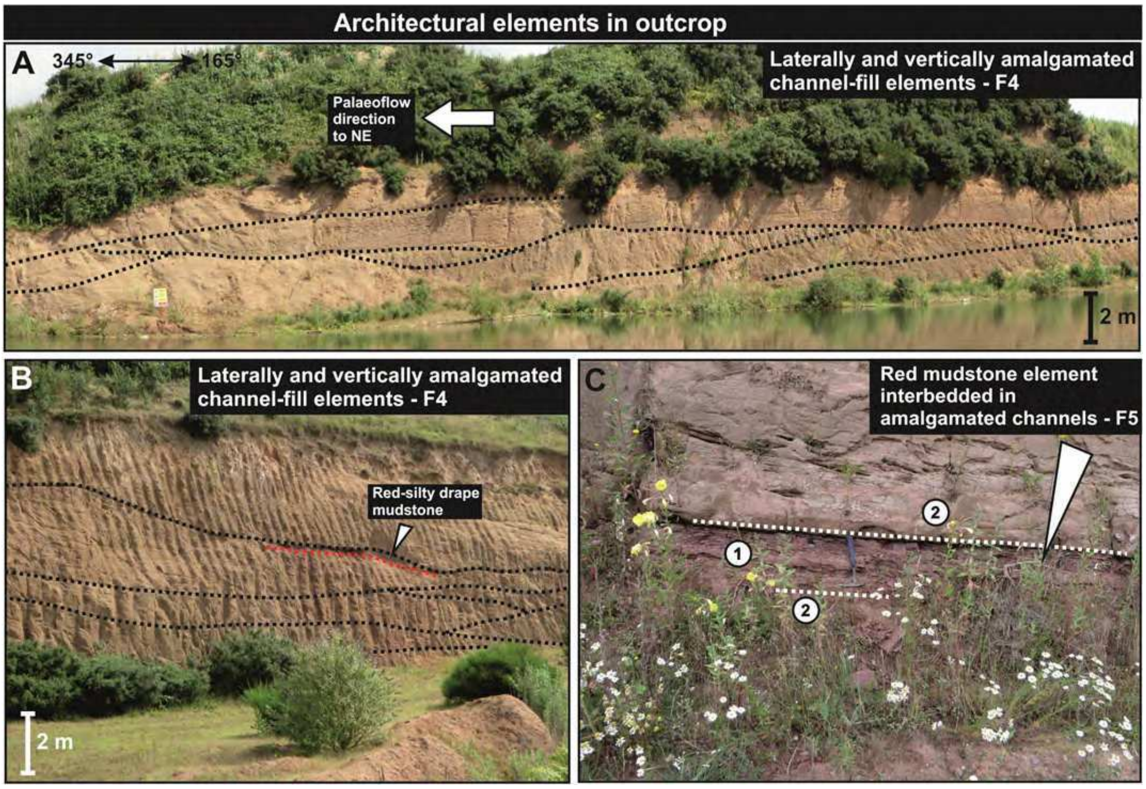

Architectural elements in outcrop
A 345° 165°
Laterally and vertically amalgamated channel-fill elements - F4
Palaeoflow direction to NE
2 m
B
Laterally and vertically amalgamated channel-fill elements - F4
Red-silty drape mudstone
2 m
C
Red mudstone element interbedded in amalgamated channels - F5
1
2
2

Fig.11

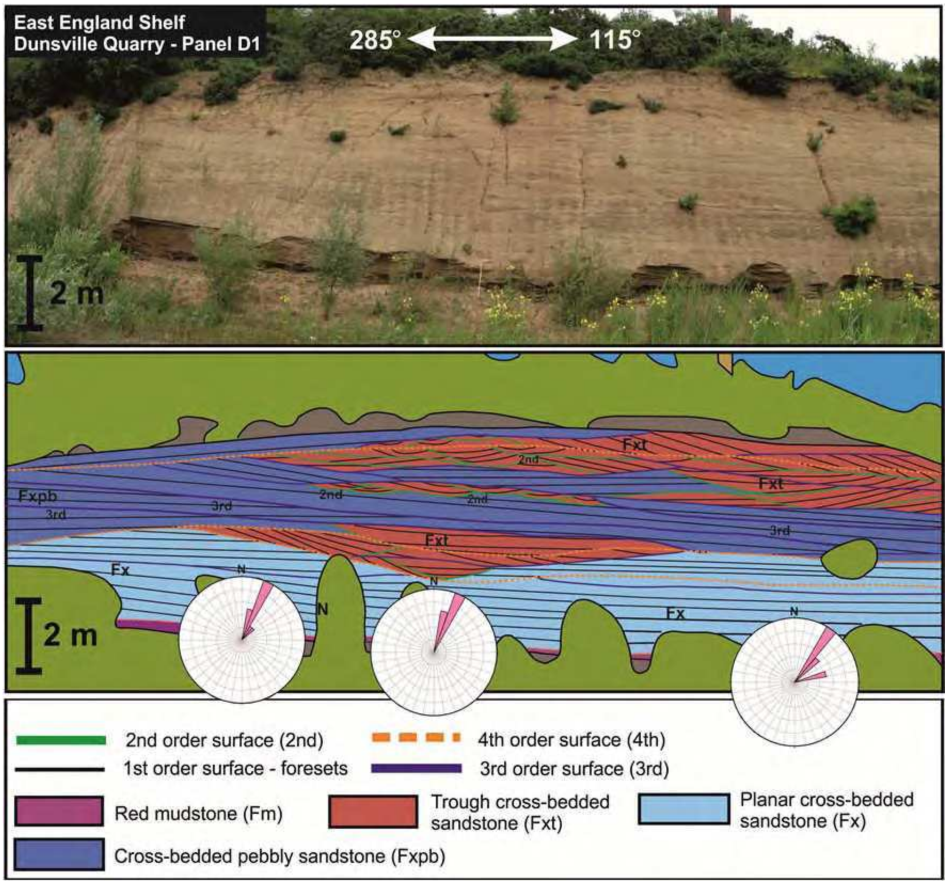

East England Shelf
Dunsville Quarry - Panel D1
285° 115°
2 m
Fxt
2nd
Fxt
Fxpb
3rd
3rd
2nd
2nd
3rd
Fxt
Fx
N
N
Fx
2 m
2nd order surface (2nd)
1st order surface - foresets
4th order surface (4th)
3rd order surface (3rd)
Red mudstone (Fm)
Trough cross-bedded sandstone (Fxt)
Planar cross-bedded sandstone (Fx)
Cross-bedded pebbly sandstone (Fxpb)

Fig.12

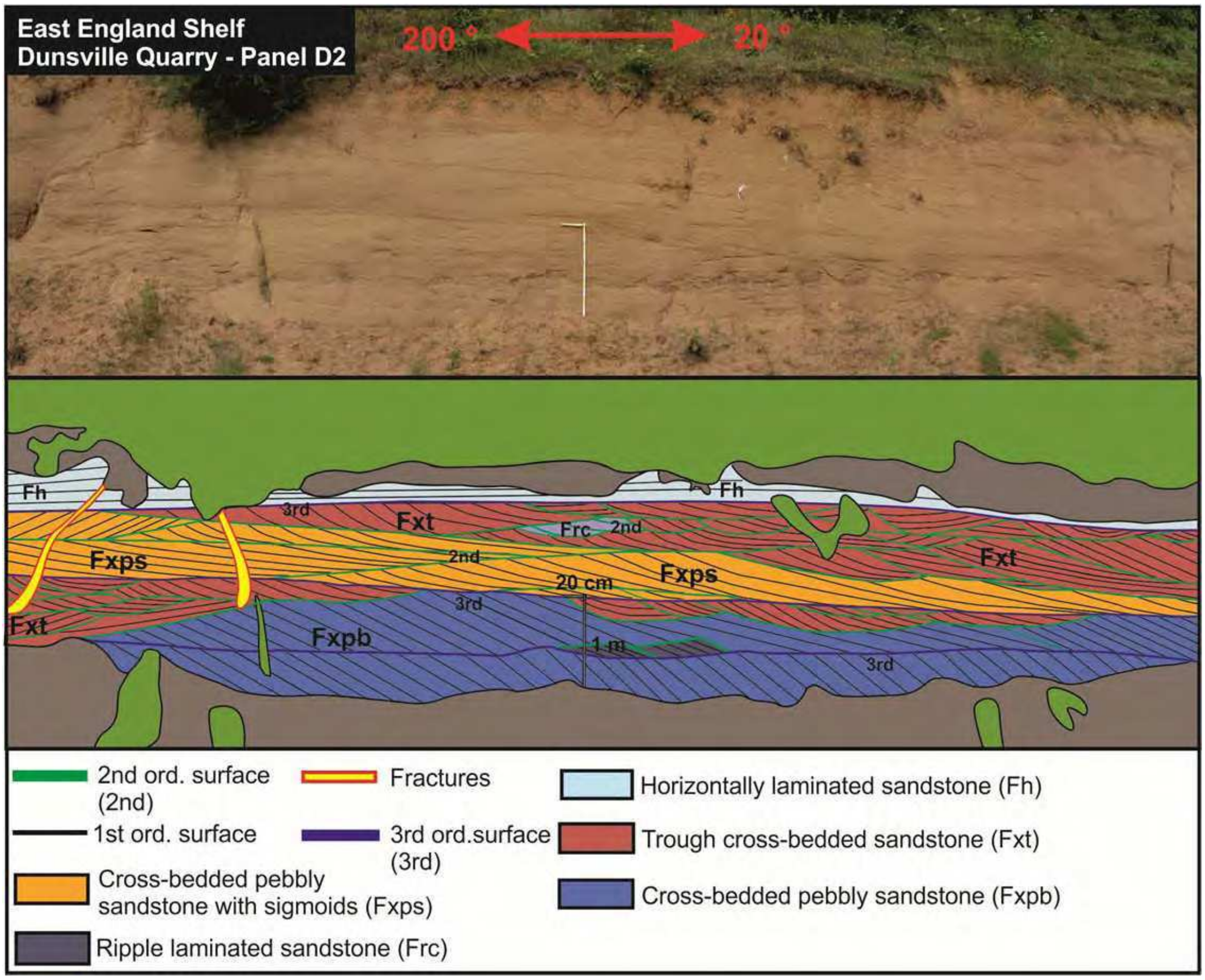

East England Shelf
Dunsville Quarry - Panel D2
200 °
20 °
Fh
3rd
Fxt
Frc
2nd
Fxps
2nd
20 cm
Fxps
Fxt
Fxt
3rd
Fxpb
1 m
3rd
2nd ord. surface (2nd)
Fractures
Horizontally laminated sandstone (Fh)
1st ord. surface
3rd ord.surface (3rd)
Trough cross-bedded sandstone (Fxt)
Cross-bedded pebbly sandstone with sigmoids (Fxps)
Cross-bedded pebbly sandstone (Fxpb)
Ripple laminated sandstone (Frc)

Fig.13

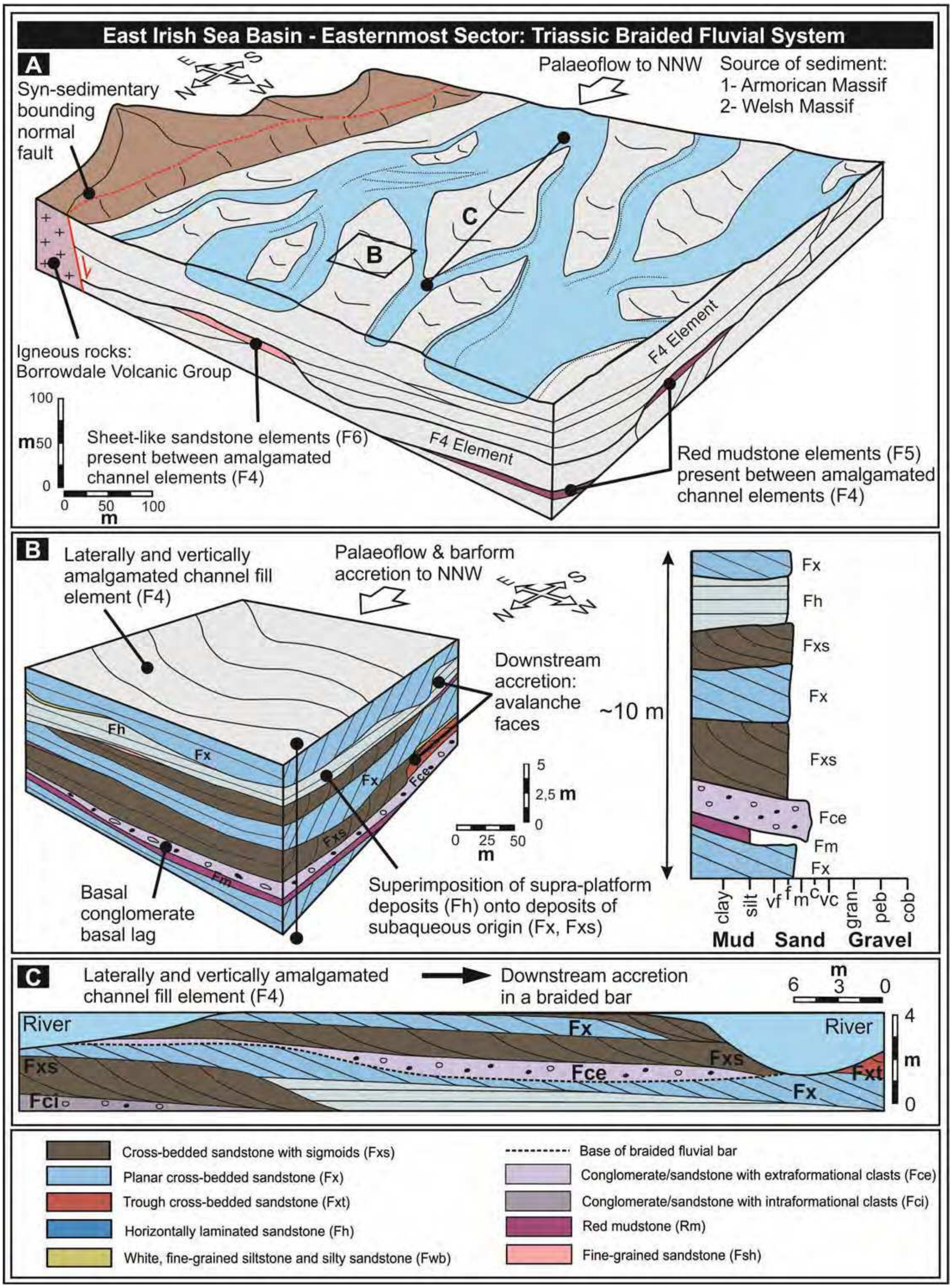

East Irish Sea Basin - Easternmost Sector: Triassic Braided Fluvial System
A
Syn-sedimentary bounding normal fault
Palaeoflow to NNW
Source of sediment:
1- Armorican Massif
2- Welsh Massif
C
B
Igneous rocks: Borrowdale Volcanic Group
F4 Element
Sheet-like sandstone elements (F6) present between amalgamated channel elements (F4)
F4 Element
Red mudstone elements (F5) present between amalgamated channel elements (F4)
B
Laterally and vertically amalgamated channel fill element (F4)
Palaeoflow & barform accretion to NNW
Downstream accretion: avalanche faces
~10 m
Fh
Fx
Fxs
Fce
Fm
Basal conglomerate basal lag
Superimposition of supra-platform deposits (Fh) onto deposits of subaqueous origin (Fx, Fxs)
clay silt vf f m c vc gran peb cob
Mud Sand Gravel
C
Laterally and vertically amalgamated channel fill element (F4)
Downstream accretion in a braided bar
River
River
Fx
Fxs
Fce
Fxt
Fci
Cross-bedded sandstone with sigmoids (Fxs)
Planar cross-bedded sandstone (Fx)
Trough cross-bedded sandstone (Fxt)
Horizontally laminated sandstone (Fh)
White, fine-grained siltstone and silty sandstone (Fwb)
Base of braided fluvial bar
Conglomerate/sandstone with extraformational clasts (Fce)
Conglomerate/sandstone with intraformational clasts (Fci)
Red mudstone (Rm)
Fine-grained sandstone (Fsh)

Fig.14

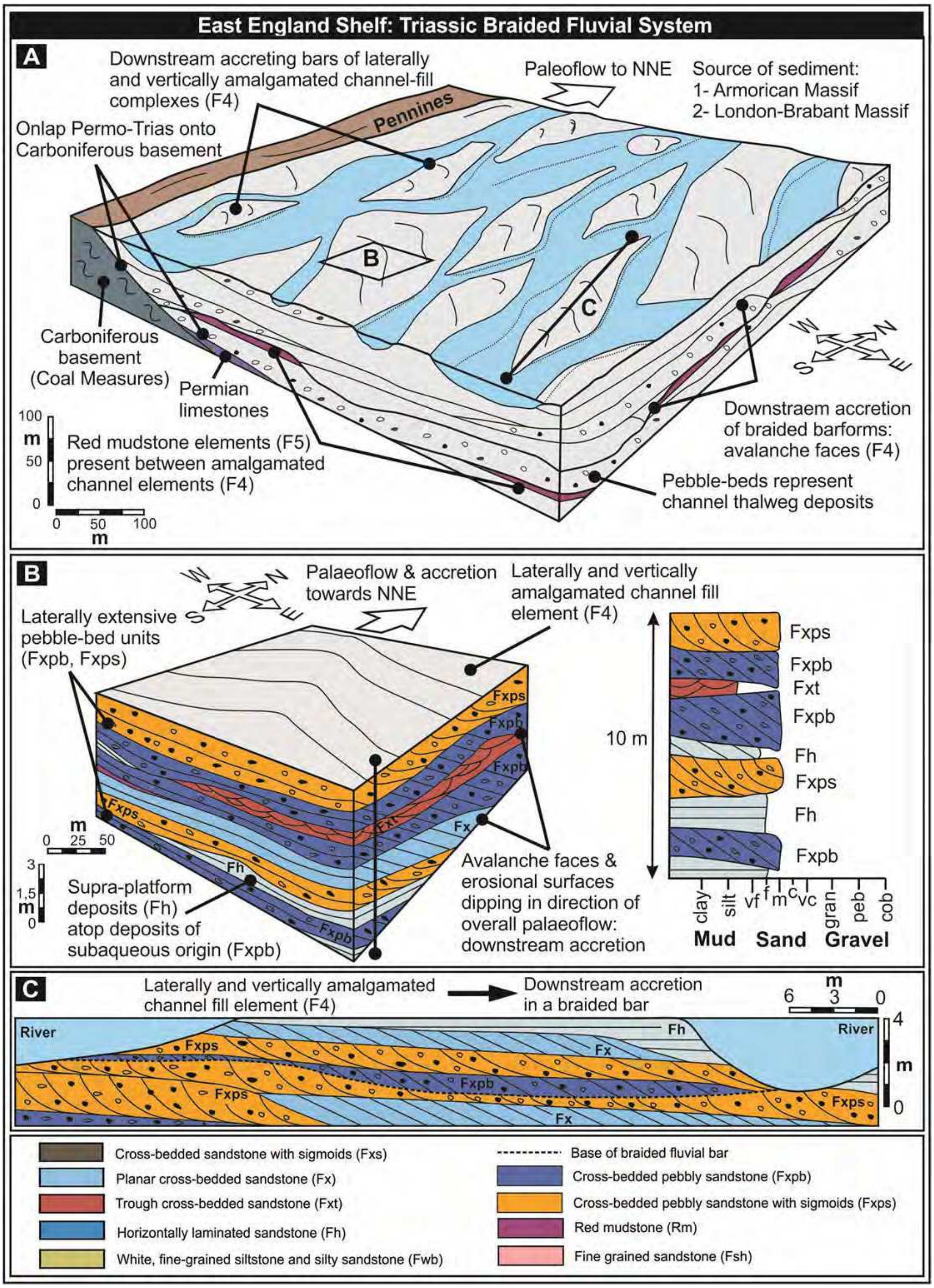

East England Shelf: Triassic Braided Fluvial System
A
Downstream accreting bars of laterally and vertically amalgamated channel-fill complexes (F4)
Paleoflow to NNE
Source of sediment:
1- Armorican Massif
2- London-Brabant Massif
Pennines
Onlap Permo-Trias onto Carboniferous basement
B
C
Carboniferous basement (Coal Measures)
Permian limestones
W
N
S
E
Downstraem accretion of braided barforms: avalanche faces (F4)
100
m
50
0
Red mudstone elements (F5) present between amalgamated channel elements (F4)
Pebble-beds represent channel thalweg deposits
0 50 100
m
B
Palaeoflow & accretion towards NNE
Laterally and vertically amalgamated channel fill element (F4)
Laterally extensive pebble-bed units (Fxpb, Fxps)
Fxps
Fxpb
Fxt
Fxpb
Fxps
Fxpb
Fxt
Fx
10 m
Fh
Fxps
Fh
Fxpb
m
0 25 50
3
1,5
m
0
Fh
Supra-platform deposits (Fh) atop deposits of subaqueous origin (Fxpb)
Avalanche faces & erosional surfaces dipping in direction of overall palaeoflow: downstream accretion
Fxpb
clay
silt
vf
f
m
c
vc
gran
peb
cob
Mud
Sand
Gravel
C
Laterally and vertically amalgamated channel fill element (F4)
Downstream accretion in a braided bar
m
6 3 0
4
m
0
River
Fxps
Fh
Fx
Fxpb
Fxps
Fxps
Fx
River
Cross-bedded sandstone with sigmoids (Fxs)
Planar cross-bedded sandstone (Fx)
Trough cross-bedded sandstone (Fxt)
Horizontally laminated sandstone (Fh)
White, fine-grained siltstone and silty sandstone (Fwb)
Base of braided fluvial bar
Cross-bedded pebbly sandstone (Fxpb)
Cross-bedded pebbly sandstone with sigmoids (Fxps)
Red mudstone (Rm)
Fine grained sandstone (Fsh)

Fig.15