Sedimentary flow heterogeneities in the Triassic UK Sherwood Sandstone Group: Insights for hydrocarbon exploration

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Abstract

Fluvial and aeolian sedimentary successions host important hydrocarbon resources as well as major groundwater aquifers. This review of the lithological characteristics of Triassic fluvio-aeolian successions of the Sherwood Sandstone Group (UK) demonstrates how distance from a fluvial sediment source and rate of rift-related tectonic subsidence play important roles in governing reservoir quality in continental successions. Increasing distance from the fluvial sediment source area results in increased porosity and permeability in deposits of mixed fluvial and aeolian reservoir successions that accumulated in arid and semi-arid settings. Indeed, successions of the UK Sherwood Sandstone Group reveal an increase in the proportion of highly permeable deposits of aeolian origin with increasing distance from the principal uplands, represented by the Armorican Massif in northern France, which formed the main source for delivery of fluvial sediment to a series of rift basins. A progressive reduction in the discharge of fluvial systems entering and passing through a series of interlinked rift basins encouraged aeolian accumulation in more distal basins. Extensional tectonics enabled preservation of highly permeable aeolian facies in basins subject to high rates (> ~100 m/Myr) of tectonic subsidence by rapidly placing such deposits below the water table. However, successions exclusively characterized by fluvial lithofacies record decreases in both porosity and permeability with increasing distance (~250-750 km) from the sediment source due to the coupling of porosity reduction and increasing clay content.

Keywords aeolian, fluvial, heterogeneities**,** permeability, reservoir, sediment source, subsidence.

1 INTRODUCTION

Fluvial and aeolian deposits commonly form thick sedimentary successions (>1 km) in basins for which accommodation was generated in response to compressional, strike-slip and extensional tectonics, as well as thermal subsidence (Bosellini, 1989; Doglioni, 1987; Hounslow & Muttoni, 2010; Waugh, 1973). For example, continental deposits of fluvial and aeolian origin represent much of the fill of the Paradox Foreland Basin of Pennsylvanian to Permian age in Utah, USA (Condon, 1997). Fluvial sedimentary successions of Triassic to Cretaceous age characterize transtensional basins associated with Euphrates strike-slip fault system in Syria (Litak et al., 1998). Siliciclastic deposits of fluvial and aeolian origin also represent significant components of the fills of rift basins that develop extensively at the onset of Wilson Cycles during supercontinent break-up (Bosellini & Hsü, 1973; Preto, Kustatscher, & Wignall, 2010; Ruffell, McKinley, & Worden, 2002; Wilson, 1963). Examples of such continental deposits are especially well preserved in Permo-Triassic successions due to the initial phase of rifting of Pangaea. These syn-rift deposits are globally widespread; they are represented in North and South America, Europe, Africa, Asia and Australia (Jones, Somerville, & Strogen, 1988; Waugh, 1973).

Siliciclastic deposits of continental origin can serve as important hosts for hydrocarbon, geothermal and groundwater resources (Aldinucci, Gandin, & Sandrelli, 2008; Cassidy et al., 2014; McKie & Williams, 2009; Tellam & Barker, 2006). Mesozoic sedimentary successions of mixed fluvial and aeolian origin host major groundwater aquifers in Europe, as well as in North America (Olivarius et al., 2015; Swanson Bahr, Bradbury, & Anderson, 2006; Tellam, 2004). A review of their hydrogeological properties, where successions have not been subjected to significant groundwater alteration, is useful to provide information for reservoir characterization at depths > ~1 km (Medici, West, & Mountney, 2016, 2018). However, the great majority of published research on analogues of hydrocarbon reservoirs focuses on seismic and outcrop studies for sedimentary and fault structure characterization (e.g., Antonellini, Aydin, & Pollard, 1994; Miall, 2006; Torabi & Fossen, 2009), rather than on flow properties. However, previous reviews on the sedimentary heterogeneities of fluvial and aeolian successions treat allogenic factors known to influence fluvial and aeolian sedimentation (Bourquin et al., 2011; Hounslow & Ruffell, 2006, Hounslow, McKie, & Ruffell, 2012; McKie & Williams, 2009), separately from the physical properties of aquifers (Allen et al. 1997; Tellam & Barker, 2006) and reservoirs (Moraes & Surdam, 1993).

Furthermore, some studies on the hydraulic properties of such sandstones aim solely to characterize the centimetre-scale properties of the rock matrix, using core plugs (e.g., Bloomfield, Moreau, & Newell, 2006, Krystinik, 1990; Prosser & Maskall, 1993). Yet, both core plug- and well test-scale data are required jointly to effectively quantify the impact of geological heterogeneities on flow, and to guide hydrocarbon exploration in terms of drilling strategy (Corbett et al. 2012). To date, such multi-scale studies have focussed primarily on fluvial deposits at various depth intervals (Corbett, Hamidreza, & Hemant, 2012; Medici et al., 2016, 2018; Zheng, Corbett, Ryseth, & Stewart, 2000; Zheng, Corbett, & Emery, 2003). By contrast, this work reviews the multi-scale hydraulic properties of deposits of both aeolian and fluvial origin, relating them to the palaeoenvironmental setting at their time of deposition.

The absence of significant effects relating to compressional tectonics in the Triassic continental successions of NW Europe favours hydraulic characterization of sedimentary heterogeneities (Chadwick, 1997; Chadwick, Kirby, & Baily, 1994). Notably, the UK Sherwood Sandstone Group (Figure 1a, b) in NW Europe represents a continental succession representative of an active rift setting (Ziegler, 1988; Chadwick, 1997). This succession is here specifically selected for review of flow heterogeneity because a large amount of borehole information is available (Allen et al., 1997; Nirex, 1992a-c; 1993a-c; 1996a, b). Notably, a diverse suite of background hydrogeological data (e.g., matrix porosity and permeability tests, packer and pumping tests) is available for this Triassic succession for the following reasons: (i) it represents the second most important UK aquifer in terms of abstraction volume (Edmunds & Smedley, 2000); (ii) it comprises the bedrock of large industrial cities such as Birmingham, Liverpool and Manchester (Tellam & Barker, 2006); and (iii) it represents a reservoir lithology in the on-shore areas in Dorset, southern England (Worden, Benshatwan, Potts, & Elgarmadi, 2016) and offshore areas, such as the eastern Irish Sea Basin (Meadows & Beach, 1993a, b; Tyrrell, Leleu, Souders, Haughton, & Daly, 2009) and the North Sea (McKie, Jolley, & Kristensen, 2010; Nguyen et al., 2013).

The Sherwood Sandstone Group crops out in several UK Triassic basins (Figure 1b). These basins are characterized by different subsidence rates and developed at various distances from the main fluvial sediment source area, which is represented by the Armorican Massif in northern France (Morton, Hounslow, & Frei, 2013; Tyrrell, Haughton, Souders, Daly, & Shannon, 2012). Core plug- (porosity, permeability) and well test-scale (transmissivity form pumping tests) properties may be related to different palaeoenvironmental scenarios (aeolian *vs.* fluvial settings) and to different allogenic factors known to have controlled sedimentation (e.g., tectonic subsidence rate and sediment source distance). Thus, the establishment of relationships between hydraulic properties, tectonics and palaeoenvironmental factors can provide predictive information on reservoir quality (cf. Bridge, 2006).

The fundamental aim of this study of the petro-hydraulic properties of the UK Sherwood Sandstone Group is to establish the role of a range of geological processes (tectonic subsidence and distance from fluvial sediment source) on development of flow heterogeneities in siliciclastic mixed fluvial and aeolian sedimentary successions that developed under conditions of widespread climatic aridity. Specific objectives are as follows: (i) to quantify the impact on flow of sedimentary heterogeneities in continental successions; (ii) to document the control of tectonic subsidence rates on the hydraulic properties of fluvial and aeolian aquifers; and (iii) to establish the respective role of tectonic subsidence *vs*. distance from the fluvial sediment source on preservation of both aeolian and fluvial lithofacies in rift basins.

2 GEOLOGICAL FRAMEWORK OF THE TRIASSIC OF GREAT BRITAIN

The Triassic Sherwood Sandstone Group (~237-252 Myr; Induan-Ladinian) comprises a continental sedimentary succession accumulated in a series of sedimentary basins developed in the interior of the Pangaea supercontinent in response to the phase of rifting that preceded the opening of the Atlantic Ocean (Chadwick, 1997; Hounslow & Ruffell, 2006; Tyrrell et al. 2012). The majority of the accumulated deposits of the "Sherwood Sandstone" have long been ascribed to a mixed aeolian and fluvial origin (Figure 2, Bachman et al., 2010; Holliday et al., 2008; Mountney & Thompson, 2002; Newell, 2017a, b; Thompson, 1970a, b). Such fluvial deposits have been related to braided fluvial systems in the Triassic realm of Great Britain, due to the dominance of accreting barform deposits, characterized by a low spread of foreset cross-dip azimuths, and the bifurcation of flow around mid-channel longitudinal bars (Brookfield, 2004; Medici et al., 2015; Steel & Thompson, 1983; Wakefield et al., 2015).

The Sherwood Sandstone Group lies immediately above the ~7 Myr hiatus which marks the Permo-Triassic boundary in the sedimentary basins of Great Britain (Brookfield, 2004, 2008; Hounslow et al., 2017; Newell 2017a, b). Lacustrine mudstone and evaporites, alluvial fans and aeolian deposits of various Upper Permian formations underlie the Sherwood Sandstone Group below this Permo-Triassic hiatus (Figure 2). The Sherwood Sandstone Group conformably passes upwards into mudstones, gypsum and anhydrite of the Middle Triassic Mercia Mudstone Group (Figure 2; Ambrose et al., 2014; Arthurton, 1980; Brookfield, 2004; Hounslow & Ruffell, 2006; Ruffell, 1991; Ruffell & Warrington, 1998; Ruffell et al., 2016).

2.1 Tectonics

Mesozoic extensional tectonic events created several basins and elevated areas in NW Europe during the Permo-Triassic (Figure 1). Morpho-structural highs in what is now Great Britain and northern France served as a principal source of sediment for fluvial systems (Hounslow et al., 2012; McKie & Williams, 2009). Extensional tectonics continued after the Permo-Triassic climax and continued to affect basins in England throughout much of the Jurassic and Cretaceous (Chadwick, 1997; Chadwick & Evans, 1995). Since this time, NW Europe has experienced uplift during the Cenozoic, partly in response to vertical lithosphere rebound (Carminati et al., 2009), related either to seafloor spreading or to the transit of a lighter and buoyant asthenosphere underneath the European Plate (Brodie & White, 1994; Carminati et al., 2009). This vertical lithospheric uplift resulted in the development of vertical stratabound fractures (*sensu* Odling et al., 1999), which pervade much of the Sherwood Sandstone Group succession. This mechanism favours development of joints which terminate in correspondence to the horizontal bedding discontinuities (Hitchmough et al., 2007; Medici et al., 2016, 2018; Tellam & Barker, 2006).

The Sherwood Sandstone Group accumulated in a series of Permo-Triassic basins (Figure 1b): in the West Midlands of England are the Staffordshire, Needwood and Cheshire basins; in northwest England is the Vale of Eden basin; and at the border between England and Scotland is the Carlisle (or Solway) basin. All of these basins represent half-graben-type rift basins (Chadwick, 1997; Chadwick et al., 1994; Woodcock, 1984). However, in southern England, the Wessex and the Worcester basins, and in northwest England, the eastern Irish Sea Basin are grabens bounded at both margins by major normal faults (Chadwick, 1997; Griffiths 1995; Jackson & Mulholland, 1993). To the east of the Pennine hills, the Triassic succession of the eastern England Shelf represents an exception to this tectonic framework: this shelf-edge of Triassic age represents a sedimentary basin which is not bounded by extensional faults and did not experience rifting (Burley, 1984; Wakefield et al., 2015).

The above structural settings correspond to sedimentary basins that experienced different rates of tectonic subsidence. Back-stripping curves (Chadwick et al., 1994; Evans et al., 1993; Worden et al. 2016) – which were determined for the lower Triassic using apatite fission track analysis techniques – indicate how the eastern Irish Sea Basin is characterized by relatively high rates of extensional tectonic subsidence (210 m/Myr) compared to the Cheshire (140 m/Myr) and the Wessex (10 m/Myr) basins. Furthermore, Burley (1984) determined that the maximum burial depth of the Sherwood Sandstone Group in the eastern England Shelf was limited to 1000 m, at the end of the Mesozoic extensional phase, based on a study of mineralogical association of cement types. This value of maximum burial depth must be distributed over the entire Mesozoic time due to the non-rifted nature of this basin, which experienced slow but steady thermal cooling which followed the opening of the Permian Zechstein Basin (Bray et al., 1992; Green, 1989). Thus, the eastern England Shelf reached 1000 m of burial in ~185 Myr (duration of the Mesozoic time) yielding a time-averaged subsidence rate of ~5 m/Myr (Burley, 1984; Green, 1989). The eastern England Shelf represents the slowest subsiding Triassic basin of England, reflecting its structural framework, for which Triassic bounding faults are absent and subsidence related driving forces were unsupported by rifting (Griffith et al., 1995; Medici et al., 2015; Štolfová & Shannon, 2009). Here, subsidence was driven by lithospheric cooling, sediment compaction and salt withdrawal (Griffith et al., 1995; Medici et al., 2015).

A paucity of diagenetic studies, which might have been useful for the reconstruction of burial depths, means that tectonic subsidence rates of other Triassic basins in England are poorly constrained. However, the thickness of the Sherwood Sandstone succession in each Triassic sedimentary basin is well constrained by the availability of numerous seismic lines and boreholes (Allen et al., 1997; Ambrose et al., 2014; Edmunds & Smedley, 2000; Kattenthon & Pollard, 2001; Newell 2017a, b; Nirex, 1997). Furthermore, the age (Induan-Ladinian) of the Triassic Sherwood Sandstone Group succession is known from radiometric and palaeomagnetic dating, as well as stratigraphic relationships with adjacent units (Ambrose et al., 2014; BGS, 2015; Hounslow & McIntosh, 2003; Warrington et al., 1980). Thus, time-averaged rates of accommodation generation can be derived for all the Triassic basins, by dividing average thickness of the preserved sedimentary succession by the deposition time span of the Sherwood Sandstone Group (Table 1). The average thickness of the Sherwood Sandstone Group has been corrected by accounting for the amount of erosion represented by the Hardegsen Unconformity (where the climax of extensional tectonics leads to erosion due to interplays between footwall uplift, flexural warping and isostatic rebound) which has been estimated at 150 m in the onshore-areas in England (Bourquin et al., 2011; Chadwick, 1997; Evans et al., 1993; Jackson & McKenzie, 1983). This correction has been made for calculation of accommodation generation rates, because this unconformity is documented across a large part of the Triassic realm of NW Europe (Bourquin et al. 2006, 2011). Accommodation rates typically reflect the rate of tectonic subsidence related to fault-activity or thermal cooling in the UK Triassic basins (Medici et al., 2015; Ruffell & Shelton, 1999; Štolfová & Shannon, 2009).

The relation between subsidence and tectonic activity in the realms of the Sherwood Sandstone Group can be assessed by comparing tectonic subsidence, which has been determined independently via diagenetic studies (cement mineral associations) and reconstruction of back-stripping curves, with accommodation generation rates (Burley, 1984; Chadwick et al., 1994; Evans et al., 1993; Worden et al., 2016). The eastern Irish Sea Basin and the eastern England Shelf show the highest (210 m/Myr) and lowest (5 m/Myr) subsidence rates in England, respectively (Burley, 1984; Chadwick et al., 1994). These two Triassic basins also represent two end-members with regards to accommodation generation rates (Table 1). The Cheshire Basin is characterized both by relatively high tectonic subsidence (140 m/Myr) and accommodation generation rates, which are only slightly lower than those of the eastern Irish Sea Basin (Chadwick et al., 1994). However, the Carlisle, Vale of Eden, Staffordshire, Worcester and Wessex basins (see Figure 1) have been considered sedimentary basins with accommodation generation primarily determined by thermal subsidence. Despite this, episodes of intermittent rifting are documented based either on thickening of the successions in grabens, or presence of growth faults (Chadwick 1997; Chadwick et al., 1993; Griffiths et al., 1995; Jackson & Mulholland, 1993). The tectonic setting of these sedimentary basins, which are characterized by minor rifting episodes, fit the values of accommodation generation which show intermediate and relatively low values (Table 1; 30-80 m/Myr) in the Triassic realm of Great Britain.

2.2 Palaeoclimate

The assemblage of lithofacies present in the succession of the Sherwood Sandstone Group demonstrates accumulation under the influence of an arid to semi-arid climatic regime, which characterized the Permian and Triassic basins in England and SW Scotland (Figure 1) during the Early and Middle Triassic time (Brookfield, 2004, 2008; Meadows, 2006; Schmid et al., 2006). Indeed, the absence of fossils, palaeosols and root traces (rhizocretions) in the fluvial deposits of the Sherwood Sandstone Group of Induan and Olenekian age in the Carlisle, Vale of Eden and eastern Irish Sea Basin supports the inference of arid climate conditions (Ambrose & Jones 1994; Brookfield, 2004, 2008; Holliday et al., 2008; Wakefield et al., 2015). Additionally, red-beds of fluvial and aeolian affinity have widely been interpreted as indication of aridity in the Triassic deposits of NW Europe (Bourquin et al., 1998, 2006; Mader, 1982; Olivarius et al., 2015; Preto et al., 2010; Simms & Ruffell, 1989; Tucker & Benton, 1982). Indeed, 80% of Pangaea is considered to have been subject to arid and semi-arid climatic conditions during lower Triassic time (Chumkakov, 2004; Hounslow & Ruffell, 2006). Despite this, episodes of relatively seasonal wetness are postulated, due to Tethyan monsoons, which likely resulted in substantial precipitation in the highlands of the Armorican Massif (Hounslow & Ruffell, 2006; Hounslow et al., 2012; McKie & Williams, 2009). In this scenario, fluvial transport was dictated

by precipitation and run-off in distant areas which experienced a different rainfall regime to that in the receiving arid basins. Indeed, braided rivers have been identified in arid and semi-arid regions flowing over similarly long distances (~250 - 750 km) with respect to those of the Early Triassic fluvial system of Great Britain (Fotherby, 2009; Miall, 1977; Yousefi et al., 2018).
Evidence of wetter climatic conditions is present in the Sherwood Sandstone Group of the Wessex Basin in southern England (see Figures 1 and 2). Here, the appearance of rhizocretions in the uppermost part of the fluvial succession indicates a sub-humid climate during late Anisian time (Newell 2017a). However, this is likely local to this basin and cannot be used as a palaeoclimatic indicator at the scale of the entire Triassic UK Sherwood Sandstone Group. Thus, arid or semi-arid climate conditions were largely dominant during the deposition of the Triassic Sherwood Sandstone Group of Great Britain (Brookfield, 2004, 2008; Hounslow & Ruffell, 2006; McKie & Shannon, 2011; McKie & Williams, 2009; Warrington et al., 1980).

2.3 Sediment transport and provenance

Palaeocurrent data (Figure 1a) from fluvial facies are chiefly derived from cross-stratification of sand prone channel-fills (Edwards, 1967; Gaunt, 1994; Gaunt et al., 1992; Jones & Ambrose, 1994; Medici et al., 2015; Powell et al., 1992; Smith, 1990; Smith & Francis, 1967; Steel & Thompson, 1983; Wakefield et al., 2015). Palaeocurrents from fluvial channel lithofacies indicate a northward palaeoflow from the southern Wessex Basin via a series of linked basins to the eastern Irish Sea, Vale of Eden and Carlisle basins in northern regions (Brookfield, 2004; Jones & Ambrose, 1994; McKie & Williams, 2009; Newell, 2017a, b; Smith, 1990).
Mineralogical and isotopic studies confirm how the southern Armorican Massif represented the principal fluvial sediment source for the Wessex, Worcester, Staffordshire, Needwood, Cheshire, eastern Irish Sea, Carlisle and Vale of Eden basins (Fitch et al., 1966; Manger et al., 1999; Tyrrell et al., 2012). Although detailed mineralogical and isotopic analyses are not available in the eastern England Shelf, palaeocurrent evidence from fluvial strata indicate a northward transport, parallel to the axis of this shelf-edge basin as for the other Triassic basins (Figure 1a, b; Edwards, 1967; Gaunt et al., 1992; Gaunt, 1994; Powell et al., 1992; Smith and Francis, 1967). Additionally, a northward decrease in both mean grain size and maximum clast size (Allen et al., 1997; Smith & Francis, 1967; Wakefield et al., 2015) in the eastern England Shelf confirms a southern sediment source, which is likely represented by one or a combination of the Armorican or the London Brabant massifs (Figure 1). Indeed, quartzitic breccias with clasts of

similar size occur in both the southern part of the eastern England Shelf and in the Worcester, Needwood and Staffordshire basins, where isotopic and mineralogical analyses have confirmed the Armorican Massif as the principal source (Campbell-Smith, 1963; Edwards, 1967; Fitch et al., 1966; Manger et al., 1999; Tyrrell et al., 2012; Warrington et al., 1980).

Tyrrell et al. (2012) identified the southern and central part of the Armorican Massif as principal sediment source for the Triassic of the Wessex, Worcester, Staffordshire, Cheshire and eastern Irish Sea Basin based on analysis of Pb isotopic composition of K-feldspar. The Wessex Basin represents a key area for understanding the sediment provenance of the fluvial elements of the UK Sherwood Sandstone Group due to its proximity the uplands of the Armorican Massif (Figure 1). For example, heavy mineral, mineral-chemical and zircon dating analyses of the Triassic fluvial deposits of the western Wessex Basin indicate that the sediment supply patterns to the linked UK Triassic basins are complex, involving multiple distinct sub-catchment areas (Morton et al., 2013, 2016). In fact, sediments of the Sherwood Sandstone Group generally show provenance from the southern, central and northern part of the Armorican Massif, which includes the Channel Isles (Figure 1; Morton et al., 2013, 2016; Tyrrell et al., 2012). Thus, while the Armorican Massif remains the principal sediment source, a wider catchment has been identified. Notably, the sediment source extends ~200 km further north including Brittany, Normandy and the Channel Isles (Figure 1; Morton et al., 2013, 2016).

Aeolian palaeocurrent vectors derived from dune cross-stratification foreset azimuths of aeolian facies have been collected in the Needwood, Cheshire and eastern Irish Sea basins (Mountney & Thompson, 2002; Thompson, 1970a, b). Such data show bimodality, with a general pattern of north-westward and south-eastward directed aeolian dune migration which reflect seasonal changes in trade wind (Jones & Ambrose, 1994; Mader & Yardley, 1985; Mountney & Thompson, 2002). Overall, westward dune migration is dominant in the aeolian deposits of the Sherwood Sandstone Group (Figure 1; Jones & Ambrose, 1994; McKie & Williams, 2009; Mountney & Thompson, 2002; Thompson, 1970 a, b).

2.4 Regional facies associations

In the Triassic basins of England, facies associations (Figure 2) show regional variations due to varying distances from the main fluvial sediment source (Armorican Massif) as well as in response to variations in climatic conditions (McKie & Shannon, 2011; Tyrrell et al., 2012). In all the Triassic basins of England, the basal part of the Sherwood Sandstone Group is characterized by fluvial deposits, which are dominated by channelized architectural elements

(Figure 2; Ambrose et al., 2014). An overall northward decrease in mean grain-size and maximum clast size characterizes the fluvial deposits of the Sherwood Sandstone Group, reflecting the increasing distance from the fluvial sediment source (McKie & Williams, 2009; Smith, 1990). Fluvial deposits of the lower Triassic generally pass from conglomerates (LA1 Lithofacies Association 1; Figure 3A) with interbedded pebbly sandstone in the Wessex, Worcester, Staffordshire, Needwood, Cheshire and southern eastern England Shelf basins, to medium- to fine-grained sandstone (LA2 Lithofacies Association 2; Figure 3b) in the northern part of the eastern England Shelf, eastern Irish Sea Basin, Vale of Eden and Carlisle basins (Ambrose et al., 2014; Hounslow & Ruffell, 2006; McKie & Williams, 2009).

The Sherwood Sandstone Group passes upward into increasingly sand-prone deposits, which are characterized by progressively more abundant facies of exclusively aeolian origin (LA3 Lithofacies Association 3; Figures 1c, 2d, e). Arid climatic conditions were widespread across the Triassic basins of Great Britain at the time of deposition of the Sherwood Sandstone Group (Bourquin et al., 2011; Brookfield, 2004, 2008; McKie & Shannon, 2011). Thus, the upward increasing abundance of aeolian facies content must reflect either a progressive switch-off or avulsion of the southerly fluvial system (Jones & Ambrose, 1994; Meadows & Beach, 1993a, b), else a switch-on of an aeolian sediment supply that was earlier not available for transport (cf. Kocurek & Lancaster, 1999). However, avulsion of the river system alone cannot explain the upward increase in aeolian content, since this stratigraphic pattern dominates at late stages in all the UK Triassic basins, which are characterized by a mixing of fluvial and aeolian deposits (Ambrose et al., 2014; Holliday et al., 2008).

Notably, several authors identified a general northward increase in the proportion of aeolian *vs.* fluvial facies from the upper part of the Sherwood Sandstone Group (Hounslow & Ruffell, 2006; McKie & Williams, 2009; Warrington et al., 1980). Fluvial lithofacies associations are characterized by conglomerate and pebbly sandstone lithofacies (LA1), and sandstone-prone channels interbedded with floodplain mudstone (LA2). In contrast, lithofacies associations of aeolian origin (LA3) are characterized by cross-bedded dunes, fine-grained sandstone damp interdunes and siltstones of wet interdunes (see Table 2 for further detail).

This northward increase in the proportion of the succession composed of aeolian deposits in the UK Sherwood Sandstone Group is recognized both below (Figure 4a) and above (Figure 4b) the Hardegesen Unconformity (Hounslow & Ruffell, 2006; Hounslow et al., 2012; McKie & Williams, 2009). This contrast in aeolian facies content might have arisen in response to a gradual downstream reduction in the discharge of the braided fluvial systems with increasing distance from the sediment entering the arid-climate linked basin system (Jones & Ambrose, 1994; McKie & Shannon, 2011; McKie & Williams, 2009; Newell, 2017b). Although this is consistent with the overall palaeogeographic scenario for the Triassic of NW Europe, extensional tectonics may also play a role in the preferential preservation of aeolian facies. Notably, aeolian deposits are absent throughout the eastern England Shelf Basin where accommodation generation was not driven by extensional tectonics (Smith & Francis, 1967; Wakefield et al., 2015; West & Truss, 2006). Preservation of aeolian facies in the eastern Irish Sea Basin (Calder and Ormskirk Sandstone formations) and their absence in the eastern England Shelf might be related to their different rates of accommodation generation (Table 1). High rates of tectonic subsidence in tectonically active Triassic basins may have assisted long-term preservation of aeolian deposits by rapidly placing them beneath the water table (Chadwick et al., 1994; Evans et al., 1993; Rodríguez-López et al., 2014), thereby preventing later erosion (cf. Kocurek & Havholm, 1993).

Each lithofacies association (LA1, 2, 3) represents productive hydrocarbon reservoir types in NW Europe (McKie & Audretsch, 2005; McKie & Williams, 2009; Meadows et al., 1993a, b); a summary of their lithological characteristics, palaeoenvironmental interpretation and occurrence in the UK Triassic basins and in the hydrocarbon fields in the adjacent areas is provided in Table 2, which serves as reference scheme for exploration geologists.

3 OVERVIEW OF PHYSICAL PROPERTIES OF THE SHERWOOD SANDSTONE AQUIFER

3.1 Core plug-scale properties

The Sherwood Sandstone Group across Great Britain presents matrix porosity and hydraulic conductivity values ranging from 3% to 38% and 1.0×10^{-6} to 15.0 m/day, respectively (e.g., Allen et al., 1997; Bloomfield et al., 2006; Pokar et al., 2006). Notably, the petrophysical properties of the Sherwood Sandstone Group (Table 3) show regional differences between the different Triassic basins across Great Britain. Indeed, the fastest subsiding basin (the eastern Irish Sea Basin) and the slowest subsiding basin (the eastern England Shelf) are characterized by the lowest and highest porosity and matrix hydraulic conductivity values, respectively (Table 3). Other Triassic basins, which are characterized by intermediate rates of subsidence or accommodation generation rates, show intermediate porosity and core plug-scale hydraulic conductivity (Tables 1, 3).

Facies associations play a key role in determining petrophysical properties at the scale of the single basin (Figures 5a, b and 6a-g). The Cheshire, Midlands (i.e. Staffordshire, Needwood and Worcester basins, which were grouped together by Allen et al., 1997, due to similarity in terms of facies and petrophysical properties) and eastern Irish Sea basins are characterized by the occurrence of both aeolian and fluvial facies. Data from the eastern Irish Sea Basin of West Cumbria show higher values of intergranular permeability in the aeolian deposits of the Calder Sandstone Formation than in the fluvial St Bees Sandstone Formation of that basin (Figures 2, 5b). These differences in core plug-scale permeability match the systematic increases in intergranular permeability in core logs, passing from fluvial to aeolian facies in the Triassic sandstone of the Morecambe gas field in the southern part of the eastern Irish Sea Basin (see Figures 5a for location of the boreholes). This increase in permeability has been related to a paucity of intergranular clay in deposits of aeolian dune origin in the Triassic realm of NW Europe (Meadows & Beach, 1993b; Newell, 2001; Olivarius et al., 2015, 2017).

Low-permeability layers are primarily represented in the Sherwood Sandstone Group by mudstone deposits, which are related to non-confined fluvial events (Jones & Ambrose, 1994; Smith, 1990; Wakefield et al., 2015). Such layers are characterized by hydraulic conductivities ranging from 10^{-6} up to 10^{-2} m/day (with median values 2.5 x 10^{-4} to 2.5 x 10^{-5} m/day) in the eastern Irish Sea Basin, Worcester, Needwood and Staffordshire basins (Figure 6a-g), significantly lower than equivalent values for conglomeratic and sandy channel deposits of the Sherwood Sandstone Group (Figure 6d, g; Lovelock, 1977; Nirex 1993b, c, Tellam & Barker, 2006).

The eastern England Shelf, which extends for ~250 kilometres in a north-south orientation (Figures 1, 7a, b), suggests how distance from the fluvial sediment source controls both lithofacies and petrophysical properties. Here, both grain size and the relative proportion of conglomerate and pebbly sandstone vs. fine- to medium-grained sandstone progressively decreases northwards (Figure 7b; Edwards, 1967; Gaunt et al., 1992; Gaunt, 1994; Powell et al., 1992; Smith & Francis, 1967; Wakefield et al., 2015). A fining of the matrix from medium-coarse to fine-grained sandstone has been recognized in cores as well as in quarries outcrop moving from the Nottinghamshire up to the North Sea coast areas of the eastern England Shelf (Edwards, 1967; Lovelock, 1977; Rivers et al., 1996; Smith & Francis, 1967; Wakefield et al., 2015). However, reduction in coarse-grained lithofacies and grain size of the sandy matrix cannot be only related to the increasing distance from the sediment source. Other factors, such as sediment routing and filtering via intermediate sinks, might also have played a role (Bridge, 2006; Miall, 1977). Decreasing grain size with increasing distance from the southern fluvial sediment sources (Armorican and London Brabant massifs) correlates in this basin to a 10% decrease in median porosity from the southern to the northern part (Allen et al., 1997; Koukis, 1978; Pokar et al., 2006). Core plug-scale hydraulic conductivity (see K_h and K_v values annotated in Figure 7a) also significantly reduces (~70%) northwards from the pebbly sandstone lithofacies (LA1 in Figure 2a) of Nottinghamshire, to the fine- to medium-grained sandstone (LA2 in Figure 2b) of the North Sea coast, in response to the coupling of grain size and porosity reduction moving northward (Allen et al., 1997).

3.2 Well-test scale properties

Permeability at the well-test scale at shallow depths (< 150 m BGL i.e. as reflected by transmissivity from pumping tests) does not show a clear correlation with rates of tectonic subsidence and accommodation generation. Transmissivity values in the Sherwood Sandstone Group show similar values across Great Britain, i.e. median values range from 100 up to 300 m^2/day in the various Triassic basins (Allen et al., 1997; Brassington & Walthall, 1985; Medici et al., 2016). The presence of conductive fractures in the UK Sherwood Sandstone aquifer at depths <150 m below the ground surface typically precludes linkage between transmissivity and lithofacies. For example, the fluvial St Bees Sandstone (T = 20-750 m^2/day) and the aeolian Calder Sandstone (T = 100-210 m^2/day) aquifers in the eastern Irish Sea Basin, which are characterized by significantly different porosities (Figure 5b) and core plug-scale permeability values, show substantial overlap in well-test derived transmissivity (Allen et al., 1997; Brassington & Walthall, 1985; McKie & Williams, 2009; Medici et al., 2016, 2018; Tellam & Barker, 2006). Despite this, intergranular flow dominates in the Sherwood Sandstone aquifer under circumstances of either (i) particularly high intergranular porosity (Eastern England Shelf), or (ii) reduction of fracture flow with the increasing depth and lithostatic load (eastern Irish Sea Basin). Indeed, transmissivity and lithofacies are correlated only where matrix flow dominates, for example in the shallow (<150 mGBL) and highly porous Triassic Sandstone of the eastern England Shelf, and the deeper (> 150 mBGL) St Bees Sandstone aquifer of the Eastern Irish Sea Basin (Streetly et al., 2000; Tellam & Barker, 2006). The shallow (<150 mBGL) Sherwood Sandstone aquifer of the eastern England Shelf is characterized by a northward reduction in well-test transmissivity, which correlates with the contemporaneous reduction in porosity and core plug-scale hydraulic conductivity at increasing distance from the southern fluvial sediment source (Allen et al., 1997; Koukis, 1974; McKie & Williams, 2009; Pokar et al., 2006). Notably, measurements of porosity and permeability on core plugs and transmissivity from pumping tests (see Figure 7) have been tested in the eastern England Shelf at 65 and 300 different localities, respectively (Allen et al., 1997). This further supports the hypothesis that increasing distance for the principal sediment source influences the lithological and hydraulic properties of the fluvial deposits of this shelf-edge basin.

Correlation between transmissivity and lithofacies was detected in the St Bees Sandstone aquifer at depths > 150 m, i.e. where fracture flow is relatively unimportant (Medici et al., 2016, 2018; Streetly et al., 2000). Here, the deep St Bees Sandstone aquifer of the eastern Irish Sea Basin is characterized by lower well test-scale permeability values in the basal 90 m of stratigraphic section (North Head Member) which has significant mudstone interlayers (about 25% of the thickness of the succession), compared to that of the more homogeneous (5% mudstone) upper part of the formation as represented by the South Head Member (Jones & Ambrose, 1994; Medici et al., 2015).

4 DISCUSSION

The Triassic Sherwood Sandstone Group was deposited under conditions of relative aridity, which allowed deposition of up to ~ 500-m-thick aeolian sequences in north-western England, matching the presence of aeolian dune facies in the lower Triassic in other parts of the UK (Ambrose et al., 2014; Brookfield, 2004, 2008; Hounslow & Ruffell, 2006; Mountney et al., 2002; Smith, 1990), the Netherlands (Geluk, 2005), Denmark (Olivarius et al., 2015), Germany (Mader, 1982; Bourquin, 2007), Czech Republic (Ulicny, 2004) and Poland (Grdzinski, 2005). The majority of sediment provenance studies recognize the Armorican Massif in northern France as the principal sediment source for the Sherwood Sandstone Group. This likely arises from the wide areal extent of this Variscan Orogen (Figure 1; Fitch et al., 1966; Manger et al., 1999; McKie & Williams, 2009; Morton et al., 2013, 2016; Tyrrell et al., 2012; Wills, 1948). Thus, the Triassic Sherwood Sandstone Group serves as a natural laboratory to test the role of tectonic subsidence and sediment source distance in successions of fluvial and aeolian origin under conditions of aridity (Medici et al., 2018; Tellam & Barker, 2006).

A likely control by tectonic subsidence on the physical properties of the Sherwood Sandstone aquifer appears evident by comparing the half-graben basin of the eastern Irish Sea with the shelf-edge basin of the eastern England Shelf. The faster subsiding eastern Irish Sea Basin and the slower subsiding eastern England Shelf are characterized by the lowest and highest porosity and matrix permeability values, respectively (Table 3).

The distribution of aeolian facies in UK Triassic basins of Great Britain also suggests how the interplay between tectonics and distance from the fluvial sediment source (Figure 4) plays an important role on preservation of high-permeability deposits of aeolian dune origin, and how such deposits influence reservoir quality (Ambrose et al., 2014; Jones & Ambrose, 1994; Olivarius et al., 2015). Several authors have previously highlighted a progressive northward increase in the proportion of aeolian lithofacies from the Triassic of the Wessex Basin in southern England (Otter Sandstone Formation), to the Vale of Eden, eastern Irish Sea Basin and Carlisle basins in northern England (Figure 4; Ambrose et al., 2014; Brookfield, 2004, 2008; Hounslow & Ruffell, 2006; Jones & Ambrose, 1994; McKie & Williams, 2009; Purvis & Wright, 1991). This increase in the proportion of aeolian lithofacies can be interpreted through a transitional downstream reduction in the discharge (and thereby sediment carrying capacity) of the braided fluvial system with increasing distance from the fluvial sediment source (Jones & Ambrose, 1994; Newell, 2017b), thereby providing a potential local sediment source available for aeolian reworking. At the same time, extensional tectonics likely played a secondary role in determining the preservation of aeolian facies by enabling subsidence-controlled aeolian accumulation in many basins (cf. Gawthorpe & Leeder, 2000; Kocurek & Havholm, 1993; Mountney, 2012).

Aeolian deposits are absent throughout the entire eastern England Shelf Basin, which represents the slowest Triassic subsidence-rate basin in the UK (Smith & Francis, 1967; Wakefield et al., 2015; West & Truss, 2006). In contrast, preservation of aeolian facies (Figure 4) occurs at similar distance from the main sediment source in the eastern Irish Sea Basin (Jones & Ambrose, 1994). Aeolian deposits are represented in all the other UK onshore Triassic basins, which are bounded by normal faults. The absence of aeolian deposits from specific basins (such as in this case study the shelf-edge basin of the eastern England Shelf) could, in general, result from lack of sediment sources in the upwind direction, as well as slower rate of accommodation generation (Kocurek & Havholm, 1993; Rodríguez-López et al., 2014). However, absence of sediment source in the upwind direction is an unlikely alternative explanation due the presence of multiple morphological highs (London Brabant Massif, Pennines, Mid North Sea High) adjacent to the eastern England Shelf, and the bimodality of palaeowind directions (Mader & Yardley, 1985; McKie & Williams, 2009; Thompson, 1970a, b). Cross-beds of aeolian dunes in the Triassic Sherwood Sandstone Group commonly dip both towards the northwest and southeast, possibly reflecting seasonal changes in trade winds (Mader & Yardley, 1985; Holliday et al., 2008; Jones & Ambrose, 1994).

Co-contribution of the sediment source distance and tectonic subsidence rates to preservation of aeolian vs. fluvial deposits is evident in the southernmost of the Triassic basins of Great Britain, the Wessex Basin of Devon (Figure 1). Here, the Sherwood Sandstone Group is characterized by evident paucity of aeolian deposits with respect to those of fluvial origin (Figure 4a, b). The Wessex Basin is the closest between the UK Triassic basins to the principal sediment source which is represented by the Variscan upland in northern France (Morton et al., 2013; Tyrrell et al., 2012). At the same time, this basin represented (during Triassic time) a slowly subsiding basin which was characterized by low values (~ 32 m/Myr) of accommodation generation (Table. 1; Hounslow & Mackintosh, 2003; Worden et al., 2016). This arises from its tectonic history; rifting in the later parts of the Olenekian supported thermal subsidence in creating accommodation space (Newell 2017a, b; Ruffell & Shelton, 1999). Thus, the coupling of low subsidence and proximity to the fluvial sediment source do not favour aeolian preservation in the Sherwood Sandstone Group, here (Kocurek & Havholm, 1993; McKie & Williams, 2009; Rodríguez-López et al., 2014).

The interplay between subsidence rate and distance form sediment source on preservation of aeolian *vs.* fluvial deposits at the scale of the entire UK Sherwood Sandstone Group is illustrated in Figure 8. Increasing distance from the fluvial sediment source in continental deposits in rift systems tends to improve hydrocarbon reservoir quality in mixed fluvial and aeolian successions because of an increase in the proportion of relatively porous deposits of aeolian dune origin (see Figure 8 upper part). Additionally, extensional tectonics favours preservation of aeolian facies in highly subsiding basins (>100 m/Myr) enhancing their long-term preservation potential (Kocurek & Havholm, 1993). By contrast, reservoir quality reduces with increasing distance from the upland source of sediment in reservoirs of exclusively fluvial origin. This arises from progressive reduction of grain size and porosity. Such deposits show less permeable matrices moving from the intermediate (~400 km) to more distal (~750 km) parts of the studied braided fluvial system (Allen et al., 1997; Koukis, 1978). Additionally, the sandy matrix in the fluvial deposits of the Worcester, Needwood and Staffordshire ($K_{median} = 6.2\times10^{-6}$ m/day; n=410) basins is more permeable with respect to that of the eastern England Shelf ($K_{median}= 1.0\times10^{-6}$ m/day; n=1400) due to higher clay content in the latter basin (Allen et al., 1997; Ramingwong, 1977). This may arise from an increase in allochthonous clay at rising distances (> ~250 km) from the sediment feeding area (Bridge, 2006; Miall, 1977). Hence, this northward reduction in permeability seems to extend from ~250 up to ~750 km (see Figure 8 upper and lower parts) distance from the primary fluvial sediment source area (Figure 1; Morton et al., 2013, 2016).

Rapid rates of subsidence also favour preservation of mudstone beds of fluvial overbank origin since channel emplacement by avulsion has reduced potential to rework such deposits (Figure 8 central part; Colombera et al., 2015). Such overbank mudstone elements that occur interbedded with fluvial channel elements are capable of impeding flow to production wells (Medici et al., 2016, 2018). Preservation of such overbank deposits, which is favoured by high rates of extensional tectonics (> ~100 m/Myr), allows sufficient preservation in vertical section (>15% of thickness) and lateral extent (>200 m) (Colombera et al., 2013) of mudstone elements to make such bodies effective in reducing well test-scale permeability where matrix flow dominates. Thus, the preservation of such bodies serves to reduce reservoir quality (Medici et al., 2016, 2018).

6 CONCLUSIONS

Aeolian and fluvial siliciclastic sedimentary successions form thick accumulations (>1 km) in basins for which accommodation was generated in response to extensional, compressional and strike-slip tectonics, as well as thermal subsidence. These deposits, such as those of the UK Sherwood Sandstone Group, are of variable geological age and arise primarily in response to the development of rift settings associated with the break-up of supercontinents. Extensional tectonics creates uplands representing the source of sediments for much of the fill of rift basins. This review shows how distance from the main fluvial sediment source and extensional tectonics play an interlinked role in determining reservoir quality in the fluvial and mixed aeolian-fluvial successions of the Sherwood Sandstone Group. Indeed, increasing distance from the main fluvial sediment source increases reservoir quality in mixed fluvial and aeolian reservoirs that accumulated in arid or semiarid climatic settings. This is because the occurrence of highly permeable deposits of aeolian dune origin increases with distance from the point of fluvial entry into an arid basin system due to a reduction in the discharge (and associated decrease in fluvial sediment transport capacity).

Extensional tectonics also favours preservation of aeolian facies in rapidly subsiding basins (> ~100 m/Myr) by quickly placing such accumulations beneath the water table, thereby protecting them from erosion. In contrast, reservoir quality decreases with increasing distance (~250 to 750 km) from the principal upland in reservoirs of exclusively fluvial origin. This arises from progressive decrease of grain size, porosity and increase of clay content, which reduce permeability at intermediate distances form the principal sediment source. Additionally, high subsidence rates in fluvial reservoirs favour preservation of low-permeability mud-prone elements of fluvial overbank origin deposited by non-confined fluvial events which impede flow to the production wells in hydrocarbon exploration.

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Tables

Table 1. Age, thickness and accommodation generation rates for the Sherwood Sandstone Group in the UK Triassic basins

Sedimentary basin	**Time Span (Myr)**	**Average Thickness (m)**	**Accommodation Generation rate (m/Myr)**
Wessex Basin	11 Myr Hounslow and McIntosh, 2003	200 Edwards et al. (1997) Kattenthon and Pollard (2001)	32
Eastern England Shelf	9 Myr Warrington *et al.* (1980)	200 Edmunds and Smedley (2000)	22
Cheshire Basin	8 Myr Hounslow and McIntosh, 2003	750 Evans et al. (1993)	112
Needwood Basin	9 Myr BGS (2015)	350 Ambrose et al. (2014)	55
Staffordshire Basin	9 Myr Steel and Thompson (1983)	340 Warrington et al. (1980)	54
Worcester Basin	10 Myr BGS (2015)	650 Allen et al. (1997)	80
Eastern Irish Sea Basin	9 Myr Hounslow and McIntosh, 2003	1650 Nirex (1997)	183
Vale of Eden Basin	8 Myr BGS, (2015)	275 Allen et al. (1997)	53

Carlisle Basin	9 Myr Brookfield (2004)	575 Allen et al. (1997) Brookfield (2004)	80

Table 2. Lithological characteristics, palaeoenvironmental interpretation and occurrence of the principal lithofacies association in the UK Sherwood Sandstone Group.

Lithofacies association (code)	**Lithological description**	**Palaeoenvironmental Significance**	**UK Sedimentary Basin**	**Hydrocarbon Fields**	**Reference**
Conglomerate and pebbly-sandstone (LA1)	Laterally extensive and amalgamated sheets of cross-bedded and parallel laminated conglomerates, together with sand-prone interbedded lenses	Braided, bedload dominated and confined streams conglomerates. Sheets of pebbly sandstone lying between the conglomerates largely represent deposition from sandwaves and dunes.	Wessex, Staffforshire, Needwood, Cheshire, eastern England Shelf	Wytch Farm (On-shore, Dorset) Bridport (Off-shore, English Channel)	Steel and Thompson (1983) Smith (1990)
Sand-prone channels with floodplain mudstone (LA2)	Erosively based, fining upward sandbodies up to 6 m thick, dominated by cross-bedded and parallel laminated fine to medium grained sandstone beds; sandstone-prone channel elements typically occur interbedded with frequent mudstone layers at the base of the sedimentary succession	Sandstone bodies are related to braided river systems. These Sandstone-prone channel elements occur at the base of the fluvial succession interbedded with mudstones which were deposited by non-confined flood events in fluvial floodplain settings	eastern England Shelf, Carlisle, Vale of Eden, Eastern Irish Sea Basin	Corrib (Off-shore, Irish Sea) Morecambe (Off-shore, Irish Sea) Caister (Off-shore, North Sea)	Ritchie and Pratsides, 1993 Noy et al. 2012 Olivarius et al. (2015)
Aeolian sandstone (LA3)	Cross-bedded fine to medium grained sandstone; very fine-grained and bed-parallel laminated sandstone and siltstone also occur	Cross-bedded sandy dunes dominate, very fine-grained and bed-parallel-laminated sandstone of exclusively aeolian origin. Damp interdune sandstone/siltstones also occur. Rarely, siltstone laminae of wet interdunes are represented	Wessex, Staffforshire Needwood, Cheshire, Carlisle, Vale of Eden, Eastern Irish Sea	Corrib (Off-shore, Irish Sea) Morecambe (Off-shore, Irish Sea) Heron Cluster (Off-shore, North Sea)	Meadows et al. (1993 a, b) McKie and Audretsch, 2005 McKie and Williams (2009)

Table 3. Porosity (ϕ) and hydraulic conductivity (m/day) of the Sherwood Sandstone Group measured both parallel (K_h) and perpendicular (K_v) respect to the bedding for the Worcester (WB), Midland (MB), eastern England Shelf (EES), Cheshire (CB), Eastern Irish Sea (EISB), Vale of Eden (VEB), and Carlisle (CAB) basins (data from Allen et al., 1997; Bloomfield et al. 2006; Koukis, 1978; Nirex 1993a, b; Pokar et al. 2006).

Parameter	**WB (n=114)**	**MB (n=410)**	**EES (n=1400)**	**CB (n=290)**	**EISB (n=228)**	**VEB (n=50)**	**CAB (n=16)**
Maximum	ϕ = 36.0% K_h=4.3 K_v=1.2	ϕ= 36.2% K_h=15.0 K_v=12.0	ϕ= 37.4% K_h=22.5 K_v=20.5	ϕ= 34.7% K_h=4.1 K_v=3.1	ϕ= 26.3% K_h=9.4×10^{-1} K_v=2.1×10^{-1}	ϕ= 34.0% K_h=2.6×10^{-1} K_v=2.1×10^{-1}	ϕ= N/A% K_h=0.5 K_v=N/A
Minimum	ϕ=3.0% K_h=2.0×10^{-6} K_v=1.9×10^{-6}	ϕ= 3.6% K_h=6.2×10^{-5} K_v=2.0×10^{-5}	ϕ= 7.8% K_h=1.0×10^{-6} K_v=1.9×10^{-6}	ϕ= 6.2% K_h=2.3×10^{-4} K_v=1.8×10^{-4}	ϕ= 1.5% K_h=2.0×10^{-6} K_v=1.9×10^{-6}	ϕ= 19.0% K_h=0.01 K_v=5.0×10^{-3}	ϕ= N/A K_h=0.2 K_v=N/A
Median	ϕ=14.8% K_h=8.9×10^{-3} K_v=2.4×10^{-3}	ϕ= 26.9% K_h=0.61 K_v=0.28	ϕ= 28.5% K_h=0.62 K_v=0.31	ϕ= 24.0% K_h=0.21 K_v=0.11	ϕ= 12.7% K_h=2.9×10^{-3} K_v= 7.0×10^{-4}	ϕ= 27.0% K_h=0.30 K_v=0.20	ϕ=N/A K_h=0.30 K_v=N/A

Figure captions

Figure 1. Triassic palaeogeography of England and northern France (base map from GeoMappApp). (a) Fluvial and aeolian palaeocurrents (data sources are discussed in the text); (b) Triassic basins in Great Britain (from Wakefield et al., 2015): Worcester (WKB), Staffordshire (SB), Needwood (NB), eastern England Shelf (EES), Cheshire (CB), Eastern Irish Sea (EISB), Vale of Eden (VEB) and Carlisle (CAB) basins

Figure 2. Litho-stratigraphic scheme and nomenclature of the Permo-Triassic succession in sedimentary basins of Great Britain (based on Ambrose et al., 2014; Jones & Ambrose, 1994; Holliday et al., 2008; Hounslow & McKintosh, 2003; Hounslow & Morton, 2004; Hounslow & Ruffell 2006, Hounslow et al., 2017, Newell 2017b).

Figure 3. The outcropping exposure Sherwood Sandstone Group in England (see Figure 2.1b for location of sedimentary basins). (a) Conglomerate (1) and interbedded sandstone (2) sheets in the Kidderminster Sandstone Formation of the Staffordshire Basin; (b) amalgamated fluvial channels in the St Bees Sandstone Formation of the eastern Irish Sea Basin; (c) aeolian dune deposits in the Helsby Sandstone Formation in the Cheshire Basin showing soft-sediment deformation, bed-parallel and cross-laminations.

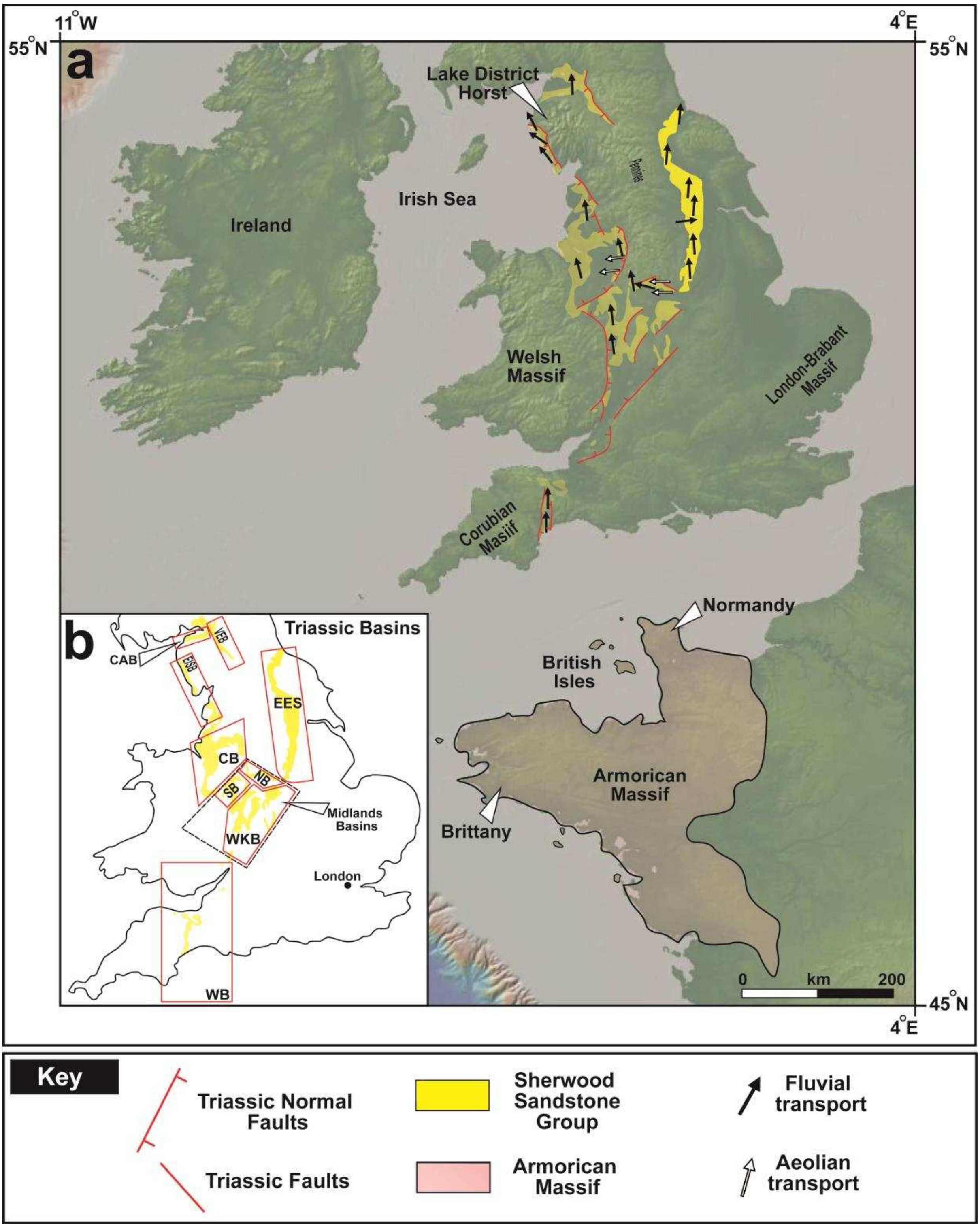
Figure 4. Proportion of fluvial *vs.* aeolian facies in the Sherwood Sandstone Group. (a) pre-Hardegsen unconformity (Ambrose et al., 2014; Bouch et al., 2006; Evans et al., 1995; Jones & Ambrose, 1984; Smith, 1990; Warrington et al., 1980), (b) Post-Hardegsen unconformity (Ambrose et al. 2014; Brookfield, 2004, 2008; Evans et al., 1995; Jones & Ambrose, 1994; Newell, 2017a; Purvis and Wright, 1991).

Figure 5. The Triassic of the Eastern Irish Sea Basin. (a) Structural map from Jackson and Mulholland (1993); black rectangles indicate locations of the Morecambe gas fields and Sellafield area from which the core-plug permeability values of the West Cumbrian Sherwood Sandstone Group are derived (basemap from GeoMappApp), (b) Aeolian and fluvial horizontal core plug-scale hydraulic conductivity values derived from the St Bees Sandstone and the Calder Sandstone formations, respectively (Allen et al. 1997; Nirex, 1992a, 1992c, 1993b, 1993c).

Figure 6. Channel sandstone and conglomerate vs. overbank mudstone in the Sherwood Sandstone aquifer. (a) Permo-Triassic deposits (PT) and Palaeozoic Igneous Metamorphic (IM) rocks in Western England and location of the Croxden and Hulme quarries, (b) Channel conglomerate (Co) and sandstone (Cs) in the Kidderminster Sandstone Formation of the Staffordshire Basin (Hulme Quarry, Stoke on Trent); (c) Overbank mudstone (Mu) interbedded with channel conglomerates (Co) in the Kidderminster Sandstone Formation of the Needwood Basin (Croxden Quarry, Cheadle); d) Core plug scale horizontal hydraulic conductivity for the conglomerate (Co), sandstone (Cs) and mudstone (Mu) of the Kidderminster Sandstone Formation in the Worcester, Staffordshire and Needwood basins (Ramingwong, 1977; Tellam & Barker, 2006); (e) Permo-Triassic deposits (PT) and Palaeozoic Igneous Metamorphic (IM) rocks in West England with location of the Fleswick Bay in West Cumbria; (f) Mudstone layers (Mu) interbedded in fluvial channels (Cs) in the St Bees Sandstone Formation of the eastern Irish Sea Basin (Fleswick Bay, St Bees); (g) Core plug-scale horizontal hydraulic conductivity in the channel sandstone (Cs) and overbank mudstone (Mu) of the St Bees Sandstone Formation in the eastern Irish Sea Basin (Sellafield area, Nirex, 1993b, c).

Figure 7. Sherwood Sandstone aquifer of the eastern England Shelf (basemap from GeoMappApp). (a) Median core plug hydraulic conductivity (Allen et al., 1997; Koukis, 1978; Pokar et al., 2006) and transmissivity ranges in the Sherwood Sandstone aquifer (from Allen et al., 1997; Rivers et al., 1996); (b) Northward variation in the relative proportion of principal lithofacies characterizing the aquifer (data from BGS, 2015; Medici et al., 2015; Taylor et al. 2003, West & Truss, 2006; Wakefield et al. 2015).

Figure 8. Fluvial and aeolian facies associations and permeability as a function of subsidence rate and distance from sediment source. Middle panel shows influence of subsidence rate on mudstone preservation in fluvial channel deposits.



11°W
4°E
55°N
55°N
a
Lake District
Horst
Irish Sea
Ireland
Pennines
Welsh
Massif
London-Brabant
Massif
Corubian
Massif
Normandy
British
Isles
Armorican
Massif
Brittany
0
km
200
45°N
4°E
b
Triassic Basins
CAB
VEB
ESB
EES
CB
NB
SB
Midlands
Basins
WKB
London
WB
Key
Triassic Normal
Faults
Triassic Faults
Sherwood
Sandstone
Group
Armorican
Massif
Fluvial
transport
Aeolian
transport

Fig. 1

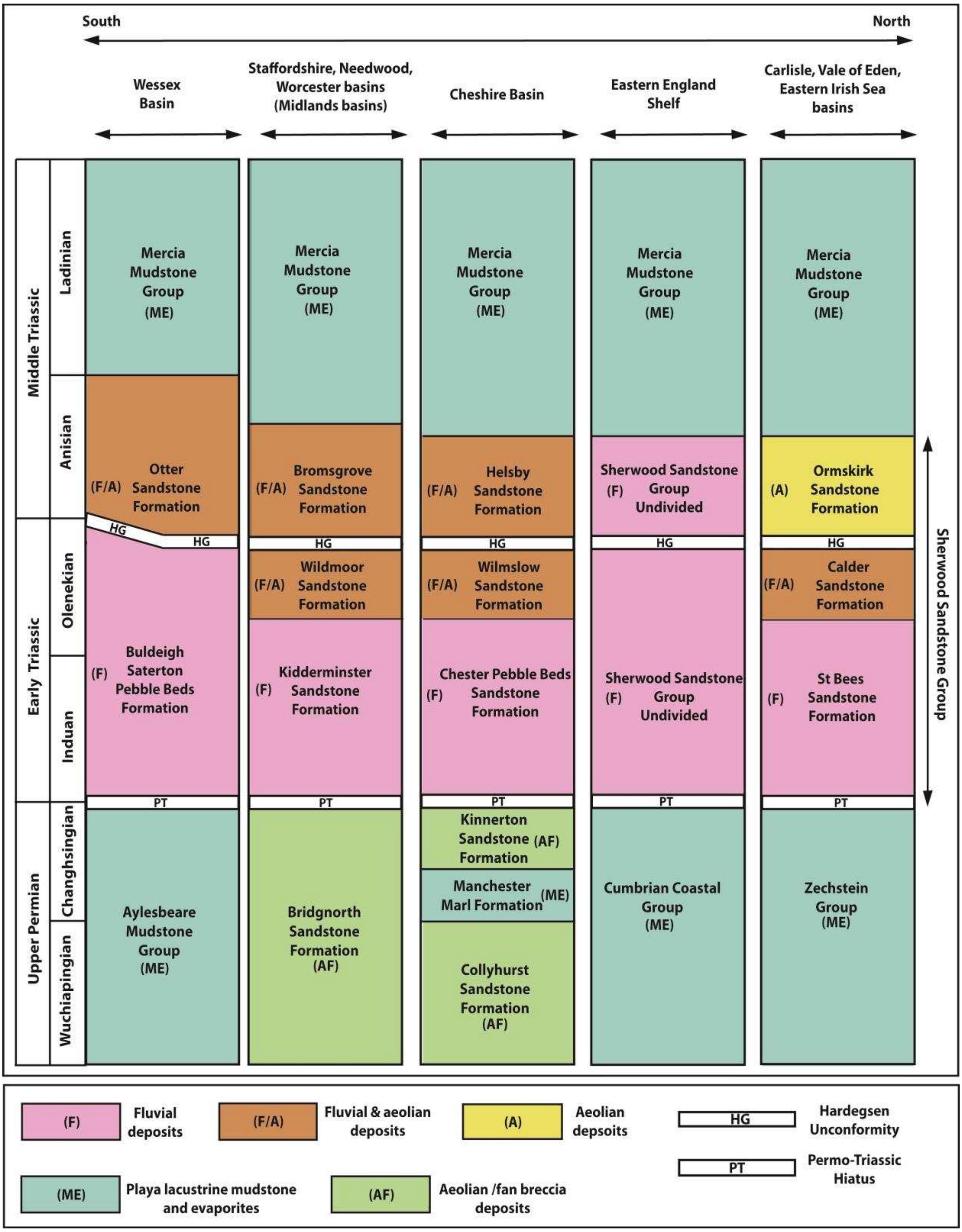

South
North
Wessex Basin
Staffordshire, Needwood, Worcester basins (Midlands basins)
Cheshire Basin
Eastern England Shelf
Carlisle, Vale of Eden, Eastern Irish Sea basins
Middle Triassic
Ladinian
Anisian
Early Triassic
Olenekian
Induan
Upper Permian
Changhsingian
Wuchiapingian
Mercia Mudstone Group (ME)
(F/A) Otter Sandstone Formation
HG
(F) Buldeigh Saterton Pebble Beds Formation
PT
Aylesbeare Mudstone Group (ME)
(F/A) Bromsgrove Sandstone Formation
(F/A) Wildmoor Sandstone Formation
(F) Kidderminster Sandstone Formation
Bridgnorth Sandstone Formation (AF)
(F/A) Helsby Sandstone Formation
(F/A) Wilmslow Sandstone Formation
(F) Chester Pebble Beds Sandstone Formation
Kinnerton Sandstone (AF) Formation
Manchester Marl Formation (ME)
Collyhurst Sandstone Formation (AF)
Sherwood Sandstone (F) Group Undivided
Cumbrian Coastal Group (ME)
(A) Ormskirk Sandstone Formation
(F/A) Calder Sandstone Formation
(F) St Bees Sandstone Formation
Zechstein Group (ME)
Sherwood Sandstone Group
(F) Fluvial deposits
(F/A) Fluvial & aeolian deposits
(A) Aeolian depsoits
HG Hardegsen Unconformity
PT Permo-Triassic Hiatus
(ME) Playa lacustrine mudstone and evaporites
(AF) Aeolian /fan breccia deposits

Fig. 2

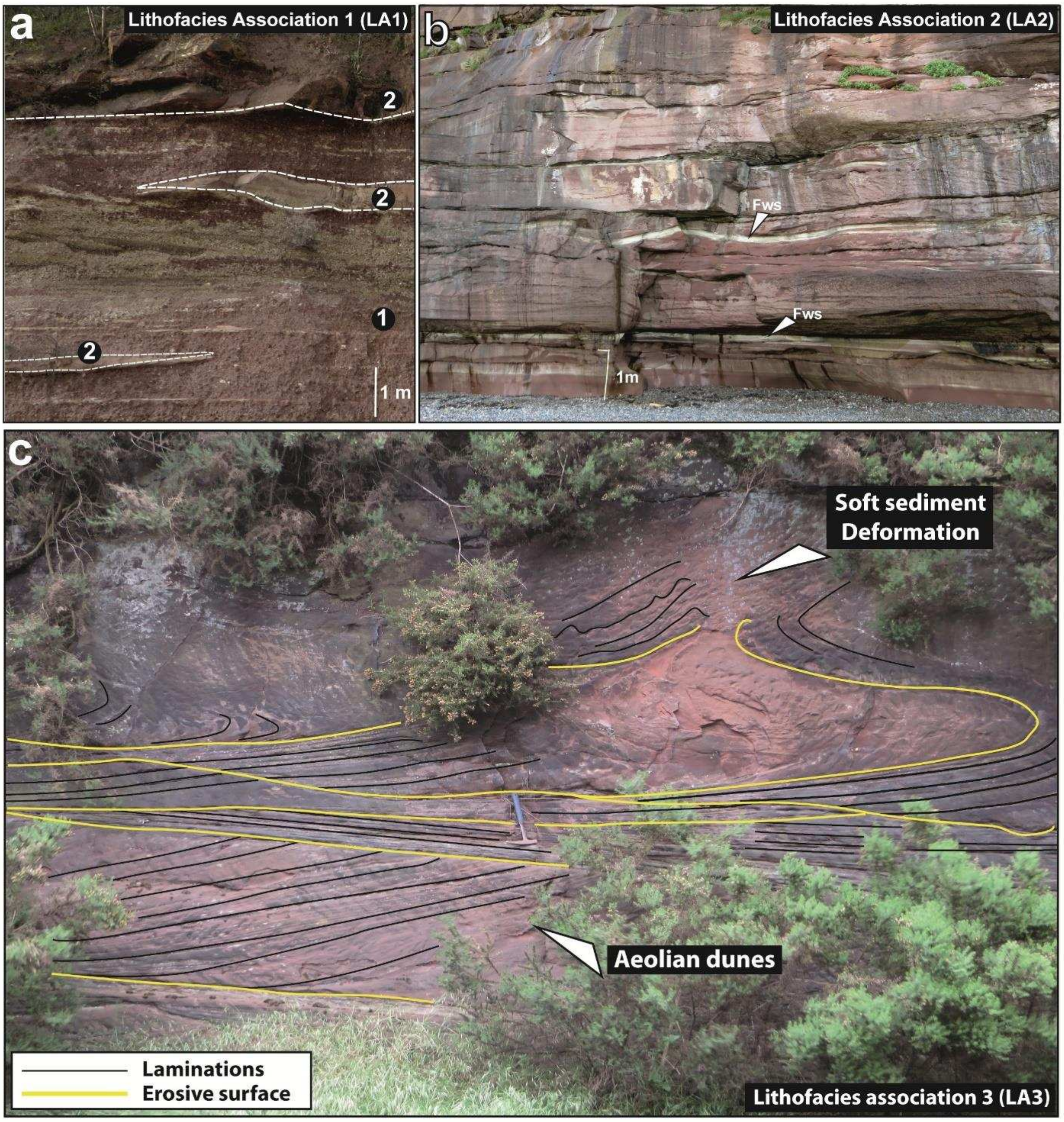

a
Lithofacies Association 1 (LA1)
2
2
1
2
1 m
b
Lithofacies Association 2 (LA2)
Fws
Fws
1m
c
Soft sediment
Deformation
Aeolian dunes
Laminations
Erosive surface
Lithofacies association 3 (LA3)

Fig. 3

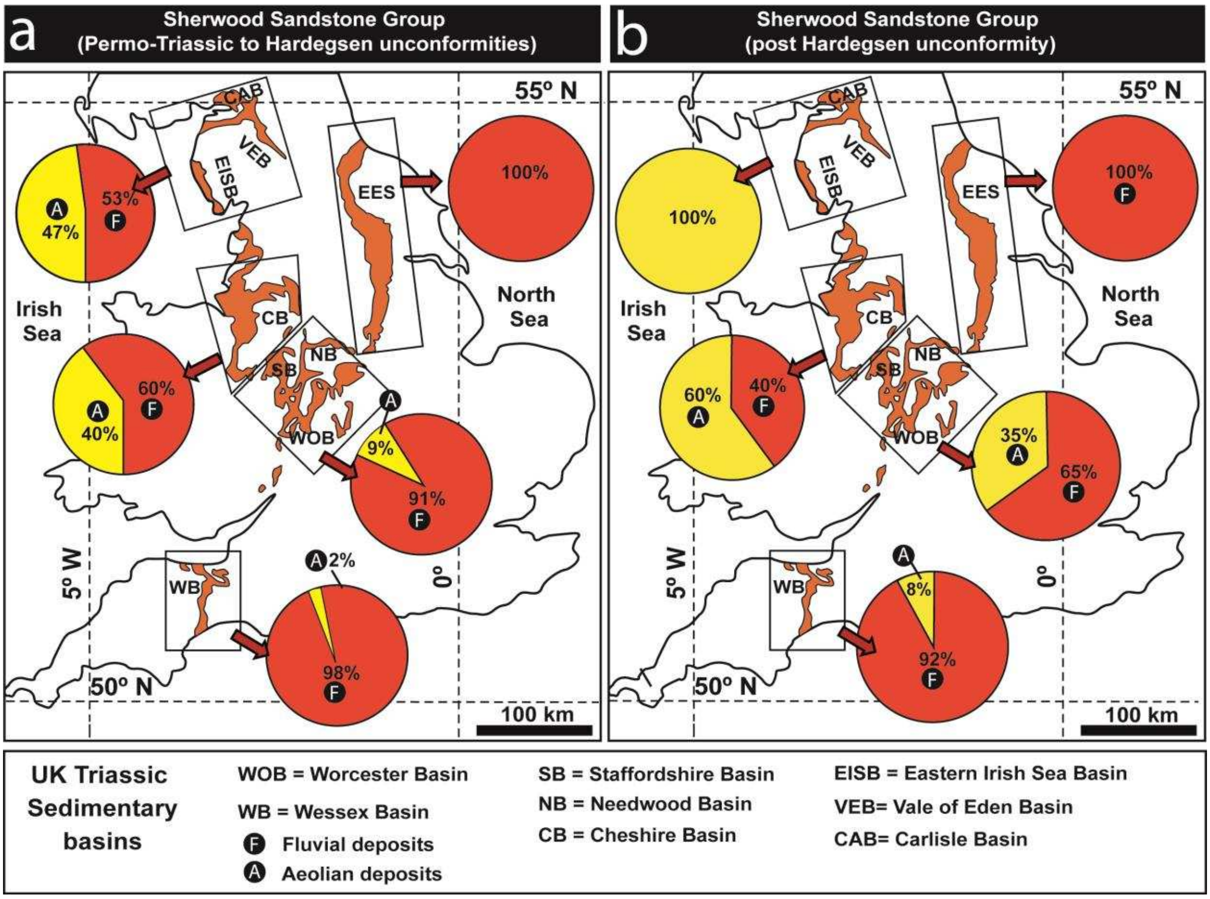

a
Sherwood Sandstone Group
(Permo-Triassic to Hardegsen unconformities)
55° N
CAB
VEB
EISB
EES
CB
NB
SB
WOB
WB
Irish Sea
North Sea
5° W
0°
50° N
100 km
53%
47%
100%
60%
40%
9%
91%
2%
98%
b
Sherwood Sandstone Group
(post Hardegsen unconformity)
100%
100%
60%
40%
35%
65%
8%
92%
UK Triassic Sedimentary basins
WOB = Worcester Basin
WB = Wessex Basin
F Fluvial deposits
A Aeolian deposits
SB = Staffordshire Basin
NB = Needwood Basin
CB = Cheshire Basin
EISB = Eastern Irish Sea Basin
VEB= Vale of Eden Basin
CAB= Carlisle Basin

Fig. 4

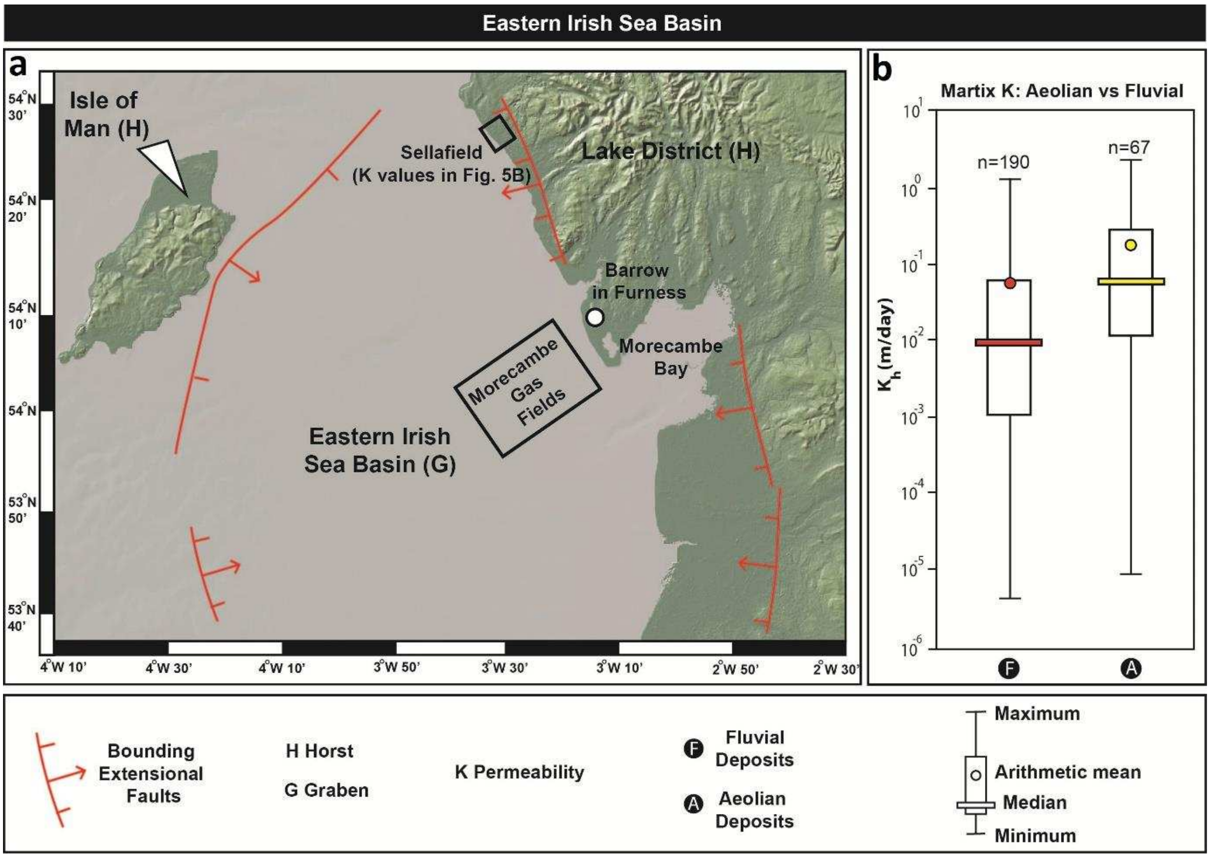
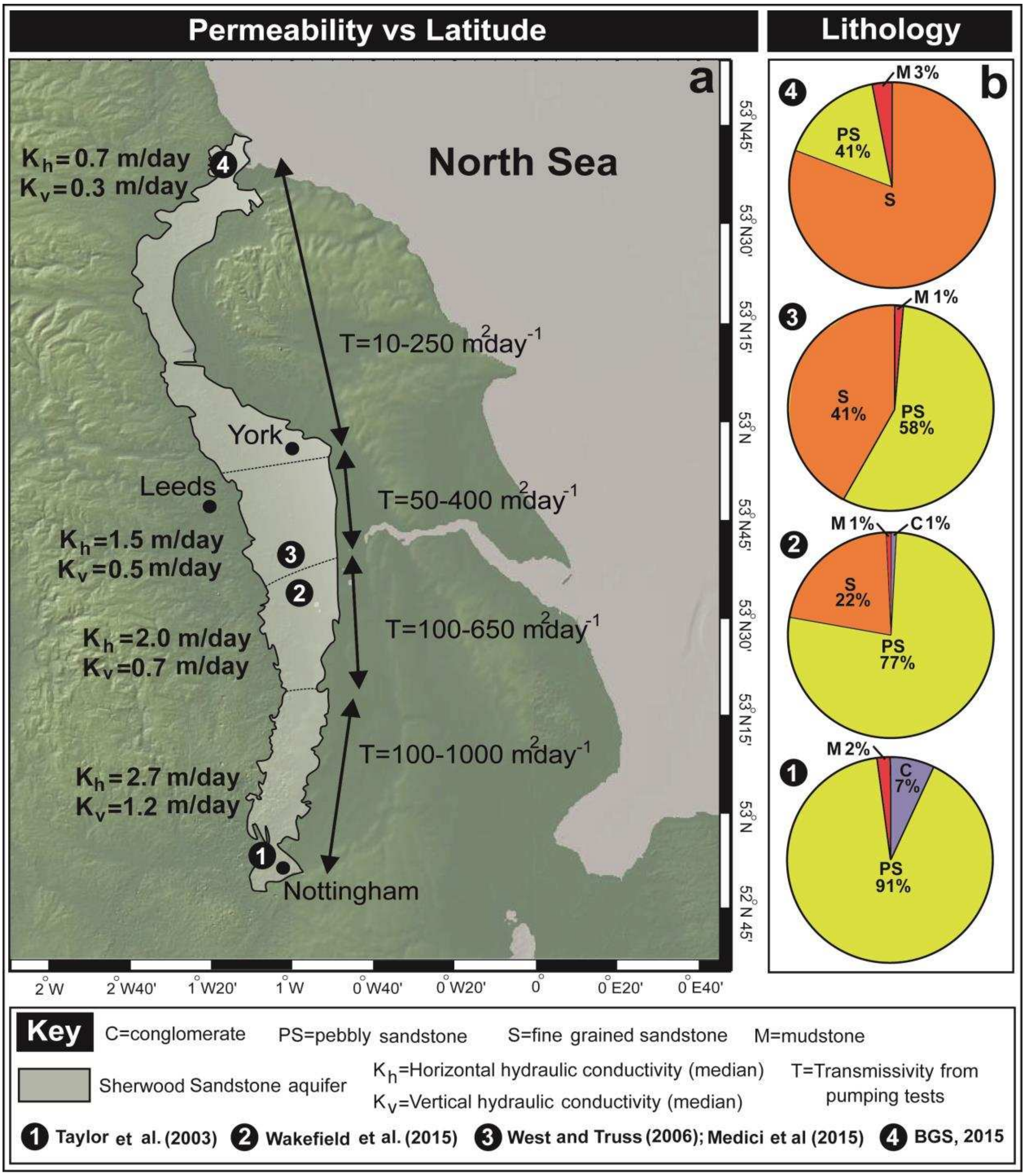

Eastern Irish Sea Basin
a
Isle of Man (H)
Sellafield
(K values in Fig. 5B)
Lake District (H)
Barrow in Furness
Morecambe Bay
Morecambe Gas Fields
Eastern Irish Sea Basin (G)
54°N 30'
54°N 20'
54°N 10'
54°N
53°N 50'
53°N 40'
4°W 10'
4°W 30'
4°W 10'
3°W 50'
3°W 30'
3°W 10'
2°W 50'
2°W 30'
b
Martix K: Aeolian vs Fluvial
n=190
n=67
K_h (m/day)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
F
A
Bounding Extensional Faults
H Horst
G Graben
K Permeability
F Fluvial Deposits
A Aeolian Deposits
Maximum
Arithmetic mean
Median
Minimum

Fig. 5

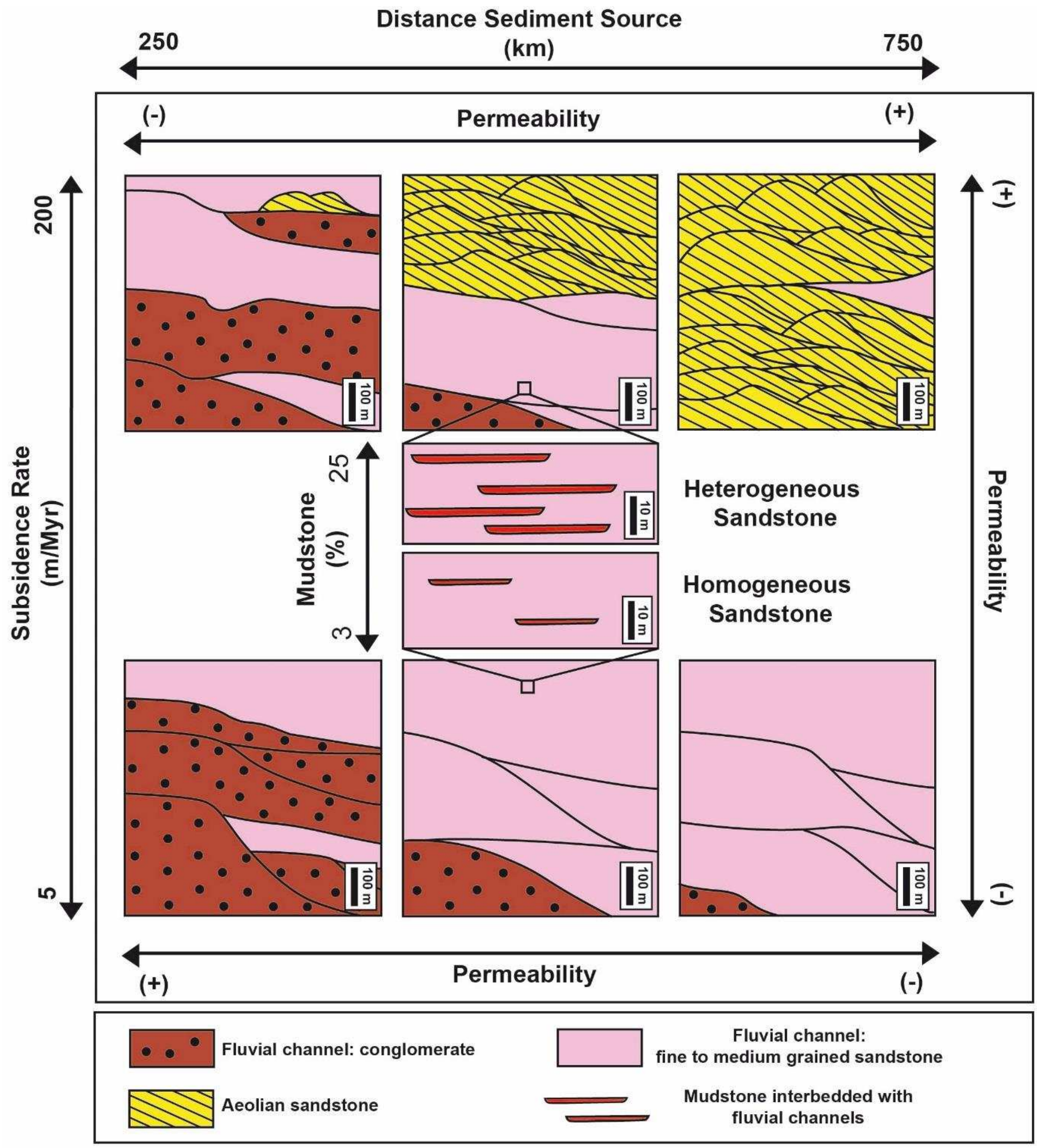
Fig. 6

Worcester, Staffordshire and Needwood Basins: Lithofacies vs. Matrix Permeability
a
53 39' N
Irish Sea
Manchester
(IM)
Cheshire Basin
Staffordshire Basin
Hulme Quarry
Croxden Quarry
Needwood Basin
(PT)
3°30' W
1°50' W
0 km 24
52°25' N
b
Co
Cs
0.6 m
Co
c
Co
Mu
1 m
Co
d
n=248
Median K_h (m/day)
6.0 m/day
1.0 m/day
2.5x10^-5 m/day
Channel Conglomerate
Co
Channel Sandstone
Cs
Mudstone (Non-Confined Flow)
Mu
Eastern Irish Sea Basin: Lithofacies vs. Matrix Permeability
e
(IM)
54 30' N
Fleswick Beach
Lake District Structural High
3°36' W
3°25' W
Eastren Irish Sea Basin
Sellafield
(PT)
0 km 5
54°23' N
f
Cs
Mu
Cs
0.20 m
g
n=127
Median K_h (m/day)
2.4x10^-2 m/day
2.5x10^-4 m/day
Channel Sandstone
Cs
Mudstone (Non-Confined Flow)
Mu



Permeability vs Latitude
Lithology
a
b
North Sea
K_h = 0.7 m/day
K_v = 0.3 m/day
T=10-250 m²day⁻¹
York
Leeds
T=50-400 m²day⁻¹
K_h = 1.5 m/day
K_v = 0.5 m/day
T=100-650 m²day⁻¹
K_h = 2.0 m/day
K_v = 0.7 m/day
T=100-1000 m²day⁻¹
K_h = 2.7 m/day
K_v = 1.2 m/day
Nottingham
M 3%
PS 41%
S
M 1%
S 41%
PS 58%
M 1%
C 1%
S 22%
PS 77%
M 2%
C 7%
PS 91%
Key
C=conglomerate
PS=pebbly sandstone
S=fine grained sandstone
M=mudstone
Sherwood Sandstone aquifer
K_h=Horizontal hydraulic conductivity (median)
K_v=Vertical hydraulic conductivity (median)
T=Transmissivity from pumping tests
1 Taylor et al. (2003)
2 Wakefield et al. (2015)
3 West and Truss (2006); Medici et al (2015)
4 BGS, 2015

Fig. 7



Distance Sediment Source
(km)
250
750
Permeability
(-)
(+)
Subsidence Rate
(m/Myr)
200
5
Mudstone
(%)
25
3
100 m
10 m
Heterogeneous
Sandstone
Homogeneous
Sandstone
Permeability
(+)
(-)
Fluvial channel: conglomerate
Aeolian sandstone
Fluvial channel:
fine to medium grained sandstone
Mudstone interbedded with
fluvial channels

Fig. 8