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1 **Sedimentary flow heterogeneities in the Triassic UK Sherwood Sandstone Group: Insights** 2 **for hydrocarbon exploration**

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11 12 **Abstract**

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

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

32 33 **1 INTRODUCTION**

34 Fluvial and aeolian deposits commonly form thick sedimentary successions (>1 km) in basins
35 for which accommodation was generated in response to compressional, strike-slip and
36 extensional tectonics, as well as thermal subsidence (Bosellini, 1989; Doglioni, 1987; Hounslow
37 & Muttoni, 2010; Waugh, 1973). For example, continental deposits of fluvial and aeolian origin
38 represent much of the fill of the Paradox Foreland Basin of Pennsylvanian to Permian age in
39 Utah, USA (Condon, 1997). Fluvial sedimentary successions of Triassic to Cretaceous age
40 characterize transtensional basins associated with Euphrates strike-slip fault system in Syria
41 (Litak et al., 1998). Siliciclastic deposits of fluvial and aeolian origin also represent significant
42 components of the fills of rift basins that develop extensively at the onset of Wilson Cycles
43 during supercontinent break-up (Bosellini & Hsü, 1973; Preto, Kustatscher, & Wignall, 2010;
44 Ruffell, McKinley, & Worden, 2002; Wilson, 1963). Examples of such continental deposits are
45 especially well preserved in Permo-Triassic successions due to the initial phase of rifting of
46 Pangaea. These syn-rift deposits are globally widespread; they are represented in North and
47 South America, Europe, Africa, Asia and Australia (Jones, Somerville, & Strogon, 1988; Waugh,
48 1973).

49 Siliciclastic deposits of continental origin can serve as important hosts for hydrocarbon,
50 geothermal and groundwater resources (Aldinucci, Gandin, & Sandrelli, 2008; Cassidy et al.,
51 2014; McKie & Williams, 2009; Tellam & Barker, 2006). Mesozoic sedimentary successions of
52 mixed fluvial and aeolian origin host major groundwater aquifers in Europe, as well as in North
53 America (Olivarius et al., 2015; Swanson Bahr, Bradbury, & Anderson, 2006; Tellam, 2004). A
54 review of their hydrogeological properties, where successions have not been subjected to
55 significant groundwater alteration, is useful to provide information for reservoir characterization
56 at depths > ~1 km (Medici, West, & Mountney, 2016, 2018). However, the great majority of
57 published research on analogues of hydrocarbon reservoirs focuses on seismic and outcrop
58 studies for sedimentary and fault structure characterization (e.g., Antonellini, Aydin, & Pollard,
59 1994; Miall, 2006; Torabi & Fossen, 2009), rather than on flow properties. However, previous
60 reviews on the sedimentary heterogeneities of fluvial and aeolian successions treat allogenic
61 factors known to influence fluvial and aeolian sedimentation (Bourquin et al., 2011; Hounslow
62 & Ruffell, 2006, Hounslow, McKie, & Ruffell, 2012; McKie & Williams, 2009), separately from
63 the physical properties of aquifers (Allen et al. 1997; Tellam & Barker, 2006) and reservoirs
64 (Moraes & Surdam, 1993).

65 Furthermore, some studies on the hydraulic properties of such sandstones aim solely to
66 characterize the centimetre-scale properties of the rock matrix, using core plugs (e.g.,
67 Bloomfield, Moreau, & Newell, 2006, Krystinik, 1990; Prosser & Maskall, 1993). Yet, both core

68 plug- and well test-scale data are required jointly to effectively quantify the impact of geological
69 heterogeneities on flow, and to guide hydrocarbon exploration in terms of drilling strategy
70 (Corbett et al. 2012). To date, such multi-scale studies have focussed primarily on fluvial
71 deposits at various depth intervals (Corbett, Hamidreza, & Hemant, 2012; Medici et al., 2016,
72 2018; Zheng, Corbett, Ryseth, & Stewart, 2000; Zheng, Corbett, & Emery, 2003). By contrast,
73 this work reviews the multi-scale hydraulic properties of deposits of both aeolian and fluvial
74 origin, relating them to the palaeoenvironmental setting at their time of deposition.

75 The absence of significant effects relating to compressional tectonics in the Triassic continental
76 successions of NW Europe favours hydraulic characterization of sedimentary heterogeneities
77 (Chadwick, 1997; Chadwick, Kirby, & Baily, 1994). Notably, the UK Sherwood Sandstone
78 Group (Figure 1a, b) in NW Europe represents a continental succession representative of an
79 active rift setting (Ziegler, 1988; Chadwick, 1997). This succession is here specifically selected
80 for review of flow heterogeneity because a large amount of borehole information is available
81 (Allen et al., 1997; Nirex, 1992a-c; 1993a-c; 1996a, b). Notably, a diverse suite of background
82 hydrogeological data (e.g., matrix porosity and permeability tests, packer and pumping tests) is
83 available for this Triassic succession for the following reasons: (i) it represents the second most
84 important UK aquifer in terms of abstraction volume (Edmunds & Smedley, 2000); (ii) it
85 comprises the bedrock of large industrial cities such as Birmingham, Liverpool and Manchester
86 (Tellam & Barker, 2006); and (iii) it represents a reservoir lithology in the on-shore areas in
87 Dorset, southern England (Worden, Benshatwan, Potts, & Elgarmadi, 2016) and offshore areas,
88 such as the eastern Irish Sea Basin (Meadows & Beach, 1993a, b; Tyrrell, Leleu, Souders,
89 Haughton, & Daly, 2009) and the North Sea (McKie, Jolley, & Kristensen, 2010; Nguyen et al.,
90 2013).

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

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

110

111

112 **2 GEOLOGICAL FRAMEWORK OF THE TRIASSIC OF GREAT BRITAIN**

113

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

125 The Sherwood Sandstone Group lies immediately above the ~7 Myr hiatus which marks the
126 Permo-Triassic boundary in the sedimentary basins of Great Britain (Brookfield, 2004, 2008;
127 Hounslow et al., 2017; Newell 2017a, b). Lacustrine mudstone and evaporites, alluvial fans and
128 aeolian deposits of various Upper Permian formations underlie the Sherwood Sandstone Group
129 below this Permo-Triassic hiatus (Figure 2). The Sherwood Sandstone Group conformably
130 passes upwards into mudstones, gypsum and anhydrite of the Middle Triassic Mercia Mudstone
131 Group (Figure 2; Ambrose et al., 2014; Arthurton, 1980; Brookfield, 2004; Hounslow & Ruffell,
132 2006; Ruffell, 1991; Ruffell & Warrington, 1998; Ruffell et al., 2016).

133

134 **2.1 Tectonics**

135
136 Mesozoic extensional tectonic events created several basins and elevated areas in NW Europe
137 during the Permo-Triassic (Figure 1). Morpho-structural highs in what is now Great Britain and
138 northern France served as a principal source of sediment for fluvial systems (Hounslow et al.,
139 2012; McKie & Williams, 2009). Extensional tectonics continued after the Permo-Triassic
140 climax and continued to affect basins in England throughout much of the Jurassic and
141 Cretaceous (Chadwick, 1997; Chadwick & Evans, 1995). Since this time, NW Europe has
142 experienced uplift during the Cenozoic, partly in response to vertical lithosphere rebound
143 (Carminati et al., 2009), related either to seafloor spreading or to the transit of a lighter and
144 buoyant asthenosphere underneath the European Plate (Brodie & White, 1994; Carminati et al.,
145 2009). This vertical lithospheric uplift resulted in the development of vertical stratabound
146 fractures (*sensu* Odling et al., 1999), which pervade much of the Sherwood Sandstone Group
147 succession. This mechanism favours development of joints which terminate in correspondence to
148 the horizontal bedding discontinuities (Hitchmough et al., 2007; Medici et al., 2016, 2018;
149 Tellam & Barker, 2006).

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

161 The above structural settings correspond to sedimentary basins that experienced different rates of
162 tectonic subsidence. Back-stripping curves (Chadwick et al., 1994; Evans et al., 1993; Worden et
163 al. 2016) – which were determined for the lower Triassic using apatite fission track analysis
164 techniques – indicate how the eastern Irish Sea Basin is characterized by relatively high rates of
165 extensional tectonic subsidence (210 m/Myr) compared to the Cheshire (140 m/Myr) and the
166 Wessex (10 m/Myr) basins. Furthermore, Burley (1984) determined that the maximum burial
167 depth of the Sherwood Sandstone Group in the eastern England Shelf was limited to 1000 m, at
168 the end of the Mesozoic extensional phase, based on a study of mineralogical association of

169 cement types. This value of maximum burial depth must be distributed over the entire Mesozoic
170 time due to the non-rifted nature of this basin, which experienced slow but steady thermal
171 cooling which followed the opening of the Permian Zechstein Basin (Bray et al., 1992; Green,
172 1989). Thus, the eastern England Shelf reached 1000 m of burial in ~185 Myr (duration of the
173 Mesozoic time) yielding a time-averaged subsidence rate of ~5 m/Myr (Burley, 1984; Green,
174 1989). The eastern England Shelf represents the slowest subsiding Triassic basin of England,
175 reflecting its structural framework, for which Triassic bounding faults are absent and subsidence
176 related driving forces were unsupported by rifting (Griffith et al., 1995; Medici et al., 2015;
177 Štolfova & Shannon, 2009). Here, subsidence was driven by lithospheric cooling, sediment
178 compaction and salt withdrawal (Griffith et al., 1995; Medici et al., 2015).

179 A paucity of diagenetic studies, which might have been useful for the reconstruction of burial
180 depths, means that tectonic subsidence rates of other Triassic basins in England are poorly
181 constrained. However, the thickness of the Sherwood Sandstone succession in each Triassic
182 sedimentary basin is well constrained by the availability of numerous seismic lines and
183 boreholes (Allen et al., 1997; Ambrose et al., 2014; Edmunds & Smedley, 2000; Kattenthon &
184 Pollard, 2001; Newell 2017a, b; Nirex, 1997). Furthermore, the age (Induan-Ladinian) of the
185 Triassic Sherwood Sandstone Group succession is known from radiometric and palaeomagnetic
186 dating, as well as stratigraphic relationships with adjacent units (Ambrose et al., 2014; BGS,
187 2015; Hounslow & McIntosh, 2003; Warrington et al., 1980). Thus, time-averaged rates of
188 accommodation generation can be derived for all the Triassic basins, by dividing average
189 thickness of the preserved sedimentary succession by the deposition time span of the Sherwood
190 Sandstone Group (Table 1). The average thickness of the Sherwood Sandstone Group has been
191 corrected by accounting for the amount of erosion represented by the Hardegsen Unconformity
192 (where the climax of extensional tectonics leads to erosion due to interplays between footwall
193 uplift, flexural warping and isostatic rebound) which has been estimated at 150 m in the onshore-
194 areas in England (Bourquin et al., 2011; Chadwick, 1997; Evans et al., 1993; Jackson &
195 McKenzie, 1983). This correction has been made for calculation of accommodation generation
196 rates, because this unconformity is documented across a large part of the Triassic realm of NW
197 Europe (Bourquin et al. 2006, 2011). Accommodation rates typically reflect the rate of tectonic
198 subsidence related to fault-activity or thermal cooling in the UK Triassic basins (Medici et al.,
199 2015; Ruffell & Shelton, 1999; Štolfova & Shannon, 2009).

200 The relation between subsidence and tectonic activity in the realms of the Sherwood Sandstone
201 Group can be assessed by comparing tectonic subsidence, which has been determined
202 independently via diagenetic studies (cement mineral associations) and reconstruction of back-

203 stripping curves, with accommodation generation rates (Burley, 1984; Chadwick et al., 1994;
204 Evans et al., 1993; Worden et al., 2016). The eastern Irish Sea Basin and the eastern England
205 Shelf show the highest (210 m/Myr) and lowest (5 m/Myr) subsidence rates in England,
206 respectively (Burley, 1984; Chadwick et al., 1994). These two Triassic basins also represent two
207 end-members with regards to accommodation generation rates (Table 1). The Cheshire Basin is
208 characterized both by relatively high tectonic subsidence (140 m/Myr) and accommodation
209 generation rates, which are only slightly lower than those of the eastern Irish Sea Basin
210 (Chadwick et al., 1994). However, the Carlisle, Vale of Eden, Staffordshire, Worcester and
211 Wessex basins (see Figure 1) have been considered sedimentary basins with accommodation
212 generation primarily determined by thermal subsidence. Despite this, episodes of intermittent
213 rifting are documented based either on thickening of the successions in grabens, or presence of
214 growth faults (Chadwick 1997; Chadwick et al., 1993; Griffiths et al., 1995; Jackson &
215 Mulholland, 1993). The tectonic setting of these sedimentary basins, which are characterized by
216 minor rifting episodes, fit the values of accommodation generation which show intermediate and
217 relatively low values (Table 1; 30-80 m/Myr) in the Triassic realm of Great Britain.

218

219 **2.2 Palaeoclimate**

220

221 The assemblage of lithofacies present in the succession of the Sherwood Sandstone Group
222 demonstrates accumulation under the influence of an arid to semi-arid climatic regime, which
223 characterized the Permian and Triassic basins in England and SW Scotland (Figure 1) during the
224 Early and Middle Triassic time (Brookfield, 2004, 2008; Meadows, 2006; Schmid et al., 2006).
225 Indeed, the absence of fossils, palaeosols and root traces (rhizocretions) in the fluvial deposits of
226 the Sherwood Sandstone Group of Induan and Olenekian age in the Carlisle, Vale of Eden and
227 eastern Irish Sea Basin supports the inference of arid climate conditions (Ambrose & Jones
228 1994; Brookfield, 2004, 2008; Holliday et al., 2008; Wakefield et al., 2015). Additionally, red-
229 beds of fluvial and aeolian affinity have widely been interpreted as indication of aridity in the
230 Triassic deposits of NW Europe (Bourquin et al., 1998, 2006; Mader, 1982; Olivarius et al.,
231 2015; Preto et al., 2010; Simms & Ruffell, 1989; Tucker & Benton, 1982). Indeed, 80% of
232 Pangaea is considered to have been subject to arid and semi-arid climatic conditions during
233 lower Triassic time (Chumkakov, 2004; Hounslow & Ruffell, 2006). Despite this, episodes of
234 relatively seasonal wetness are postulated, due to Tethyan monsoons, which likely resulted in
235 substantial precipitation in the highlands of the Armorican Massif (Hounslow & Ruffell, 2006;
236 Hounslow et al., 2012; McKie & Williams, 2009). In this scenario, fluvial transport was dictated

237 by precipitation and run-off in distant areas which experienced a different rainfall regime to that
238 in the receiving arid basins. Indeed, braided rivers have been identified in arid and semi-arid
239 regions flowing over similarly long distances (~250 - 750 km) with respect to those of the Early
240 Triassic fluvial system of Great Britain (Fotherby, 2009; Miall, 1977; Yousefi et al., 2018).
241 Evidence of wetter climatic conditions is present in the Sherwood Sandstone Group of the
242 Wessex Basin in southern England (see Figures 1 and 2). Here, the appearance of rhizocretions
243 in the uppermost part of the fluvial succession indicates a sub-humid climate during late Anisian
244 time (Newell 2017a). However, this is likely local to this basin and cannot be used as a
245 palaeoclimatic indicator at the scale of the entire Triassic UK Sherwood Sandstone Group. Thus,
246 arid or semi-arid climate conditions were largely dominant during the deposition of the Triassic
247 Sherwood Sandstone Group of Great Britain (Brookfield, 2004, 2008; Hounslow & Ruffell,
248 2006; McKie & Shannon, 2011; McKie & Williams, 2009; Warrington et al., 1980).

249

250

251 **2.3 Sediment transport and provenance**

252

253 Palaeocurrent data (Figure 1a) from fluvial facies are chiefly derived from cross-stratification of
254 sand prone channel-fills (Edwards, 1967; Gaunt, 1994; Gaunt et al., 1992; Jones & Ambrose,
255 1994; Medici et al., 2015; Powell et al., 1992; Smith, 1990; Smith & Francis, 1967; Steel &
256 Thompson, 1983; Wakefield et al., 2015). Palaeocurrents from fluvial channel lithofacies
257 indicate a northward palaeoflow from the southern Wessex Basin via a series of linked basins to
258 the eastern Irish Sea, Vale of Eden and Carlisle basins in northern regions (Brookfield, 2004;
259 Jones & Ambrose, 1994; McKie & Williams, 2009; Newell, 2017a, b; Smith, 1990).

260 Mineralogical and isotopic studies confirm how the southern Armorican Massif represented the
261 principal fluvial sediment source for the Wessex, Worcester, Staffordshire, Needwood, Cheshire,
262 eastern Irish Sea, Carlisle and Vale of Eden basins (Fitch et al., 1966; Manger et al., 1999;
263 Tyrrell et al., 2012). Although detailed mineralogical and isotopic analyses are not available in
264 the eastern England Shelf, palaeocurrent evidence from fluvial strata indicate a northward
265 transport, parallel to the axis of this shelf-edge basin as for the other Triassic basins (Figure 1a,
266 b; Edwards, 1967; Gaunt et al., 1992; Gaunt, 1994; Powell et al., 1992; Smith and Francis,
267 1967). Additionally, a northward decrease in both mean grain size and maximum clast size
268 (Allen et al., 1997; Smith & Francis, 1967; Wakefield et al., 2015) in the eastern England Shelf
269 confirms a southern sediment source, which is likely represented by one or a combination of the
270 Armorican or the London Brabant massifs (Figure 1). Indeed, quartzitic breccias with clasts of

271 similar size occur in both the southern part of the eastern England Shelf and in the Worcester,
272 Needwood and Staffordshire basins, where isotopic and mineralogical analyses have confirmed
273 the Armorican Massif as the principal source (Campbell-Smith, 1963; Edwards, 1967; Fitch et
274 al., 1966; Manger et al., 1999; Tyrrell et al., 2012; Warrington et al., 1980).
275 Tyrrell et al. (2012) identified the southern and central part of the Armorican Massif as principal
276 sediment source for the Triassic of the Wessex, Worcester, Staffordshire, Cheshire and eastern
277 Irish Sea Basin based on analysis of Pb isotopic composition of K-feldspar. The Wessex Basin
278 represents a key area for understanding the sediment provenance of the fluvial elements of the
279 UK Sherwood Sandstone Group due to its proximity the uplands of the Armorican Massif
280 (Figure 1). For example, heavy mineral, mineral-chemical and zircon dating analyses of the
281 Triassic fluvial deposits of the western Wessex Basin indicate that the sediment supply patterns
282 to the linked UK Triassic basins are complex, involving multiple distinct sub-catchment areas
283 (Morton et al., 2013, 2016). In fact, sediments of the Sherwood Sandstone Group generally show
284 provenance from the southern, central and northern part of the Armorican Massif, which
285 includes the Channel Isles (Figure 1; Morton et al., 2013, 2016; Tyrrell et al., 2012). Thus, while
286 the Armorican Massif remains the principal sediment source, a wider catchment has been
287 identified. Notably, the sediment source extends ~200 km further north including Brittany,
288 Normandy and the Channel Isles (Figure 1; Morton et al., 2013, 2016).
289 Aeolian palaeocurrent vectors derived from dune cross-stratification foreset azimuths of aeolian
290 facies have been collected in the Needwood, Cheshire and eastern Irish Sea basins (Mountney &
291 Thompson, 2002; Thompson, 1970a, b). Such data show bimodality, with a general pattern of
292 north-westward and south-eastward directed aeolian dune migration which reflect seasonal
293 changes in trade wind (Jones & Ambrose, 1994; Mader & Yardley, 1985; Mountney &
294 Thompson, 2002). Overall, westward dune migration is dominant in the aeolian deposits of the
295 Sherwood Sandstone Group (Figure 1; Jones & Ambrose, 1994; McKie & Williams, 2009;
296 Mountney & Thompson, 2002; Thompson, 1970 a, b).

297

298 **2.4 Regional facies associations**

299

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

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

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

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

333 This northward increase in the proportion of the succession composed of aeolian deposits in the
334 UK Sherwood Sandstone Group is recognized both below (Figure 4a) and above (Figure 4b) the
335 Hardegesen Unconformity (Hounslow & Ruffell, 2006; Hounslow et al., 2012; McKie &
336 Williams, 2009). This contrast in aeolian facies content might have arisen in response to a
337 gradual downstream reduction in the discharge of the braided fluvial systems with increasing
338 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).

372 Facies associations play a key role in determining petrophysical properties at the scale of the
373 single basin (Figures 5a, b and 6a-g). The Cheshire, Midlands (i.e. Staffordshire, Needwood and
374 Worcester basins, which were grouped together by Allen et al., 1997, due to similarity in terms
375 of facies and petrophysical properties) and eastern Irish Sea basins are characterized by the
376 occurrence of both aeolian and fluvial facies. Data from the eastern Irish Sea Basin of West
377 Cumbria show higher values of intergranular permeability in the aeolian deposits of the Calder
378 Sandstone Formation than in the fluvial St Bees Sandstone Formation of that basin (Figures 2,
379 5b). These differences in core plug-scale permeability match the systematic increases in
380 intergranular permeability in core logs, passing from fluvial to aeolian facies in the Triassic
381 sandstone of the Morecambe gas field in the southern part of the eastern Irish Sea Basin (see
382 Figures 5a for location of the boreholes). This increase in permeability has been related to a
383 paucity of intergranular clay in deposits of aeolian dune origin in the Triassic realm of NW
384 Europe (Meadows & Beach, 1993b; Newell, 2001; Olivarius et al., 2015, 2017).

385 Low-permeability layers are primarily represented in the Sherwood Sandstone Group by
386 mudstone deposits, which are related to non-confined fluvial events (Jones & Ambrose, 1994;
387 Smith, 1990; Wakefield et al., 2015). Such layers are characterized by hydraulic conductivities
388 ranging from 10^{-6} up to 10^{-2} m/day (with median values 2.5×10^{-4} to 2.5×10^{-5} m/day) in the
389 eastern Irish Sea Basin, Worcester, Needwood and Staffordshire basins (Figure 6a-g),
390 significantly lower than equivalent values for conglomeratic and sandy channel deposits of the
391 Sherwood Sandstone Group (Figure 6d, g; Lovelock, 1977; Nirex 1993b, c, Tellam & Barker,
392 2006).

393 The eastern England Shelf, which extends for ~250 kilometres in a north-south orientation
394 (Figures 1, 7a, b), suggests how distance from the fluvial sediment source controls both
395 lithofacies and petrophysical properties. Here, both grain size and the relative proportion of
396 conglomerate and pebbly sandstone vs. fine- to medium-grained sandstone progressively
397 decreases northwards (Figure 7b; Edwards, 1967; Gaunt et al., 1992; Gaunt, 1994; Powell et al.,
398 1992; Smith & Francis, 1967; Wakefield et al., 2015). A fining of the matrix from medium-
399 coarse to fine-grained sandstone has been recognized in cores as well as in quarries outcrop
400 moving from the Nottinghamshire up to the North Sea coast areas of the eastern England Shelf
401 (Edwards, 1967; Lovelock, 1977; Rivers et al., 1996; Smith & Francis, 1967; Wakefield et al.,
402 2015). However, reduction in coarse-grained lithofacies and grain size of the sandy matrix
403 cannot be only related to the increasing distance from the sediment source. Other factors, such as
404 sediment routing and filtering via intermediate sinks, might also have played a role (Bridge,
405 2006; Miall, 1977). Decreasing grain size with increasing distance from the southern fluvial

406 sediment sources (Armorican and London Brabant massifs) correlates in this basin to a 10%
407 decrease in median porosity from the southern to the northern part (Allen et al., 1997; Koukis,
408 1978; Pokar et al., 2006). Core plug-scale hydraulic conductivity (see K_h and K_v values
409 annotated in Figure 7a) also significantly reduces (~70%) northwards from the pebbly sandstone
410 lithofacies (LA1 in Figure 2a) of Nottinghamshire, to the fine- to medium-grained sandstone
411 (LA2 in Figure 2b) of the North Sea coast, in response to the coupling of grain size and porosity
412 reduction moving northward (Allen et al., 1997).

413

414 **3.2 Well-test scale properties**

415

416 Permeability at the well-test scale at shallow depths (< 150 m BGL i.e. as reflected by
417 transmissivity from pumping tests) does not show a clear correlation with rates of tectonic
418 subsidence and accommodation generation. Transmissivity values in the Sherwood Sandstone
419 Group show similar values across Great Britain, i.e. median values range from 100 up to 300
420 m^2/day in the various Triassic basins (Allen et al., 1997; Brassington & Walthall, 1985; Medici
421 et al., 2016). The presence of conductive fractures in the UK Sherwood Sandstone aquifer at
422 depths <150 m below the ground surface typically precludes linkage between transmissivity and
423 lithofacies. For example, the fluvial St Bees Sandstone ($T = 20\text{-}750 \text{ m}^2/\text{day}$) and the aeolian
424 Calder Sandstone ($T = 100\text{-}210 \text{ m}^2/\text{day}$) aquifers in the eastern Irish Sea Basin, which are
425 characterized by significantly different porosities (Figure 5b) and core plug-scale permeability
426 values, show substantial overlap in well-test derived transmissivity (Allen et al., 1997;
427 Brassington & Walthall, 1985; McKie & Williams, 2009; Medici et al., 2016, 2018; Tellam &
428 Barker, 2006). Despite this, intergranular flow dominates in the Sherwood Sandstone aquifer
429 under circumstances of either (i) particularly high intergranular porosity (Eastern England
430 Shelf), or (ii) reduction of fracture flow with the increasing depth and lithostatic load (eastern
431 Irish Sea Basin). Indeed, transmissivity and lithofacies are correlated only where matrix flow
432 dominates, for example in the shallow (<150 mBGL) and highly porous Triassic Sandstone of
433 the eastern England Shelf, and the deeper (> 150 mBGL) St Bees Sandstone aquifer of the
434 Eastern Irish Sea Basin (Streetly et al., 2000; Tellam & Barker, 2006). The shallow (<150
435 mBGL) Sherwood Sandstone aquifer of the eastern England Shelf is characterized by a
436 northward reduction in well-test transmissivity, which correlates with the contemporaneous
437 reduction in porosity and core plug-scale hydraulic conductivity at increasing distance from the
438 southern fluvial sediment source (Allen et al., 1997; Koukis, 1974; McKie & Williams, 2009;
439 Pokar et al., 2006). Notably, measurements of porosity and permeability on core plugs and

440 transmissivity from pumping tests (see Figure 7) have been tested in the eastern England Shelf at
441 65 and 300 different localities, respectively (Allen et al., 1997). This further supports the
442 hypothesis that increasing distance for the principal sediment source influences the lithological
443 and hydraulic properties of the fluvial deposits of this shelf-edge basin.

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

452

453 **4 DISCUSSION**

454

455 The Triassic Sherwood Sandstone Group was deposited under conditions of relative aridity,
456 which allowed deposition of up to ~ 500-m-thick aeolian sequences in north-western England,
457 matching the presence of aeolian dune facies in the lower Triassic in other parts of the UK
458 (Ambrose et al., 2014; Brookfield, 2004, 2008; Hounslow & Ruffell, 2006; Mountney et al.,
459 2002; Smith, 1990), the Netherlands (Geluk, 2005), Denmark (Olivarius et al., 2015), Germany
460 (Mader, 1982; Bourquin, 2007), Czech Republic (Ulicny, 2004) and Poland (Grdzinski, 2005).
461 The majority of sediment provenance studies recognize the Armorican Massif in northern France
462 as the principal sediment source for the Sherwood Sandstone Group. This likely arises from the
463 wide areal extent of this Variscan Orogen (Figure 1; Fitch et al., 1966; Manger et al., 1999;
464 McKie & Williams, 2009; Morton et al., 2013, 2016; Tyrrell et al., 2012; Wills, 1948). Thus, the
465 Triassic Sherwood Sandstone Group serves as a natural laboratory to test the role of tectonic
466 subsidence and sediment source distance in successions of fluvial and aeolian origin under
467 conditions of aridity (Medici et al., 2018; Tellam & Barker, 2006).

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

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

490 Aeolian deposits are absent throughout the entire eastern England Shelf Basin, which represents
491 the slowest Triassic subsidence-rate basin in the UK (Smith & Francis, 1967; Wakefield et al.,
492 2015; West & Truss, 2006). In contrast, preservation of aeolian facies (Figure 4) occurs at
493 similar distance from the main sediment source in the eastern Irish Sea Basin (Jones & Ambrose,
494 1994). Aeolian deposits are represented in all the other UK onshore Triassic basins, which are
495 bounded by normal faults. The absence of aeolian deposits from specific basins (such as in this
496 case study the shelf-edge basin of the eastern England Shelf) could, in general, result from lack
497 of sediment sources in the upwind direction, as well as slower rate of accommodation generation
498 (Kocurek & Havholm, 1993; Rodríguez-López et al., 2014). However, absence of sediment
499 source in the upwind direction is an unlikely alternative explanation due the presence of multiple
500 morphological highs (London Brabant Massif, Pennines, Mid North Sea High) adjacent to the
501 eastern England Shelf, and the bimodality of palaeowind directions (Mader & Yardley, 1985;
502 McKie & Williams, 2009; Thompson, 1970a, b). Cross-beds of aeolian dunes in the Triassic
503 Sherwood Sandstone Group commonly dip both towards the northwest and southeast, possibly
504 reflecting seasonal changes in trade winds (Mader & Yardley, 1985; Holliday et al., 2008; Jones
505 & Ambrose, 1994).

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

520 The interplay between subsidence rate and distance from sediment source on preservation of
521 aeolian vs. fluvial deposits at the scale of the entire UK Sherwood Sandstone Group is illustrated
522 in Figure 8. Increasing distance from the fluvial sediment source in continental deposits in rift
523 systems tends to improve hydrocarbon reservoir quality in mixed fluvial and aeolian successions
524 because of an increase in the proportion of relatively porous deposits of aeolian dune origin (see
525 Figure 8 upper part). Additionally, extensional tectonics favours preservation of aeolian facies in
526 highly subsiding basins (>100 m/Myr) enhancing their long-term preservation potential
527 (Kocurek & Havholm, 1993). By contrast, reservoir quality reduces with increasing distance
528 from the upland source of sediment in reservoirs of exclusively fluvial origin. This arises from
529 progressive reduction of grain size and porosity. Such deposits show less permeable matrices
530 moving from the intermediate (~ 400 km) to more distal (~ 750 km) parts of the studied braided
531 fluvial system (Allen et al., 1997; Koukis, 1978). Additionally, the sandy matrix in the fluvial
532 deposits of the Worcester, Needwood and Staffordshire ($K_{\text{median}} = 6.2 \times 10^{-6}$ m/day; $n=410$) basins
533 is more permeable with respect to that of the eastern England Shelf ($K_{\text{median}} = 1.0 \times 10^{-6}$ m/day;
534 $n=1400$) due to higher clay content in the latter basin (Allen et al., 1997; Ramingwong, 1977).
535 This may arise from an increase in allochthonous clay at rising distances ($> \sim 250$ km) from the
536 sediment feeding area (Bridge, 2006; Miall, 1977). Hence, this northward reduction in
537 permeability seems to extend from ~ 250 up to ~ 750 km (see Figure 8 upper and lower parts)
538 distance from the primary fluvial sediment source area (Figure 1; Morton et al., 2013, 2016).

539 Rapid rates of subsidence also favour preservation of mudstone beds of fluvial overbank origin
540 since channel emplacement by avulsion has reduced potential to rework such deposits (Figure 8
541 central part; Colombera et al., 2015). Such overbank mudstone elements that occur interbedded
542 with fluvial channel elements are capable of impeding flow to production wells (Medici et al.,
543 2016, 2018). Preservation of such overbank deposits, which is favoured by high rates of
544 extensional tectonics ($> \sim 100$ m/Myr), allows sufficient preservation in vertical section ($>15\%$
545 of thickness) and lateral extent (>200 m) (Colombera et al., 2013) of mudstone elements to make
546 such bodies effective in reducing well test-scale permeability where matrix flow dominates.
547 Thus, the preservation of such bodies serves to reduce reservoir quality (Medici et al., 2016,
548 2018).

549

550 **6 CONCLUSIONS**

551

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

566 Extensional tectonics also favours preservation of aeolian facies in rapidly subsiding basins ($>$
567 ~ 100 m/Myr) by quickly placing such accumulations beneath the water table, thereby protecting
568 them from erosion. In contrast, reservoir quality decreases with increasing distance (~ 250 to 750
569 km) from the principal upland in reservoirs of exclusively fluvial origin. This arises from
570 progressive decrease of grain size, porosity and increase of clay content, which reduce
571 permeability at intermediate distances from the principal sediment source. Additionally, high
572 subsidence rates in fluvial reservoirs favour preservation of low-permeability mud-prone

573 elements of fluvial overbank origin deposited by non-confined fluvial events which impede flow
574 to the production wells in hydrocarbon exploration.

575

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1036 **Tables**

1037 **Table 1.** Age, thickness and accommodation generation rates for the Sherwood Sandstone Group
 1038 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) Kattenhon and Pollard (2001) | 32 |
| Eastern England Shelf | 9 Myr Warrington <i>et al.</i> (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 |

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

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1040 **Table 2.** Lithological characteristics, palaeoenvironmental interpretation and occurrence of the
1041 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, Staffordshire, 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, Staffordshire 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) |

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1048 **Table 3.** Porosity (ϕ) and hydraulic conductivity (m/day) of the Sherwood Sandstone Group
 1049 measured both parallel (K_h) and perpendicular (K_v) respect to the bedding for the Worcester
 1050 (WB), Midland (MB), eastern England Shelf (EES), Cheshire (CB), Eastern Irish Sea (EISB),
 1051 Vale of Eden (VEB), and Carlisle (CAB) basins (data from Allen et al., 1997; Bloomfield et al.
 1052 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 | $\phi = 36.0\%$ $K_h=4.3$ $K_v=1.2$ | $\phi = 36.2\%$ $K_h=15.0$ $K_v=12.0$ | $\phi = 37.4\%$ $K_h=22.5$ $K_v=20.5$ | $\phi = 34.7\%$ $K_h=4.1$ $K_v=3.1$ | $\phi = 26.3\%$ $K_h=9.4 \times 10^{-1}$ $K_v=2.1 \times 10^{-1}$ | $\phi = 34.0\%$ $K_h=2.6 \times 10^{-1}$ $K_v=2.1 \times 10^{-1}$ | $\phi = \text{N/A}\%$ $K_h=0.5$ $K_v=\text{N/A}$ |
| Minimum | $\phi = 3.0\%$ $K_h=2.0 \times 10^{-6}$ $K_v=1.9 \times 10^{-6}$ | $\phi = 3.6\%$ $K_h=6.2 \times 10^{-5}$ $K_v=2.0 \times 10^{-5}$ | $\phi = 7.8\%$ $K_h=1.0 \times 10^{-6}$ $K_v=1.9 \times 10^{-6}$ | $\phi = 6.2\%$ $K_h=2.3 \times 10^{-4}$ $K_v=1.8 \times 10^{-4}$ | $\phi = 1.5\%$ $K_h=2.0 \times 10^{-6}$ $K_v=1.9 \times 10^{-6}$ | $\phi = 19.0\%$ $K_h=0.01$ $K_v=5.0 \times 10^{-3}$ | $\phi = \text{N/A}$ $K_h=0.2$ $K_v=\text{N/A}$ |
| Median | $\phi = 14.8\%$ $K_h=8.9 \times 10^{-3}$ $K_v=2.4 \times 10^{-3}$ | $\phi = 26.9\%$ $K_h=0.61$ $K_v=0.28$ | $\phi = 28.5\%$ $K_h=0.62$ $K_v=0.31$ | $\phi = 24.0\%$ $K_h=0.21$ $K_v=0.11$ | $\phi = 12.7\%$ $K_h=2.9 \times 10^{-3}$ $K_v=7.0 \times 10^{-4}$ | $\phi = 27.0\%$ $K_h=0.30$ $K_v=0.20$ | $\phi = \text{N/A}$ $K_h=0.30$ $K_v=\text{N/A}$ |

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1065 **Figure captions**

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1067 **Figure 1.** Triassic palaeogeography of England and northern France (base map from
1068 GeoMappApp). (a) Fluvial and aeolian palaeocurrents (data sources are discussed in the text);
1069 (b) Triassic basins in Great Britain (from Wakefield et al., 2015): Worcester (WKB),
1070 Staffordshire (SB), Needwood (NB), eastern England Shelf (EES), Cheshire (CB), Eastern Irish
1071 Sea (EISB), Vale of Eden (VEB) and Carlisle (CAB) basins

1072 **Figure 2.** Litho-stratigraphic scheme and nomenclature of the Permo-Triassic succession in
1073 sedimentary basins of Great Britain (based on Ambrose et al., 2014; Jones & Ambrose, 1994;
1074 Holliday et al., 2008; Hounslow & McKintosh, 2003; Hounslow & Morton, 2004; Hounslow &
1075 Ruffell 2006, Hounslow et al., 2017, Newell 2017b).

1076 **Figure 3.** The outcropping exposure Sherwood Sandstone Group in England (see Figure 2.1b for
1077 location of sedimentary basins). (a) Conglomerate (1) and interbedded sandstone (2) sheets in
1078 the Kidderminster Sandstone Formation of the Staffordshire Basin; (b) amalgamated fluvial
1079 channels in the St Bees Sandstone Formation of the eastern Irish Sea Basin; (c) aeolian dune
1080 deposits in the Helsby Sandstone Formation in the Cheshire Basin showing soft-sediment
1081 deformation, bed-parallel and cross-laminations.

1082 **Figure 4.** Proportion of fluvial vs. aeolian facies in the Sherwood Sandstone Group. (a) pre-
1083 Hardegsen unconformity (Ambrose et al., 2014; Bouch et al., 2006; Evans et al., 1995; Jones &
1084 Ambrose, 1984; Smith, 1990; Warrington et al., 1980), (b) Post-Hardegsen unconformity
1085 (Ambrose et al. 2014; Brookfield, 2004, 2008; Evans et al., 1995; Jones & Ambrose, 1994;
1086 Newell, 2017a; Purvis and Wright, 1991).

1087 **Figure 5.** The Triassic of the Eastern Irish Sea Basin. (a) Structural map from Jackson and
1088 Mulholland (1993); black rectangles indicate locations of the Morecambe gas fields and
1089 Sellafield area from which the core-plug permeability values of the West Cumbrian Sherwood
1090 Sandstone Group are derived (basemap from GeoMappApp), (b) Aeolian and fluvial horizontal
1091 core plug-scale hydraulic conductivity values derived from the St Bees Sandstone and the Calder
1092 Sandstone formations, respectively (Allen et al. 1997; Nirex, 1992a, 1992c, 1993b, 1993c).

1093 **Figure 6.** Channel sandstone and conglomerate vs. overbank mudstone in the Sherwood
1094 Sandstone aquifer. (a) Permo-Triassic deposits (PT) and Palaeozoic Igneous Metamorphic (IM)
1095 rocks in Western England and location of the Croxden and Hulme quarries, (b) Channel
1096 conglomerate (Co) and sandstone (Cs) in the Kidderminster Sandstone Formation of the
1097 Staffordshire Basin (Hulme Quarry, Stoke on Trent); (c) Overbank mudstone (Mu) interbedded
1098 with channel conglomerates (Co) in the Kidderminster Sandstone Formation of the Needwood
1099 Basin (Croxden Quarry, Cheadle); d) Core plug scale horizontal hydraulic conductivity for the
1100 conglomerate (Co), sandstone (Cs) and mudstone (Mu) of the Kidderminster Sandstone
1101 Formation in the Worcester, Staffordshire and Needwood basins (Ramingwong, 1977; Tellam &
1102 Barker, 2006); (e) Permo-Triassic deposits (PT) and Palaeozoic Igneous Metamorphic (IM)
1103 rocks in West England with location of the Fleswick Bay in West Cumbria; (f) Mudstone layers
1104 (Mu) interbedded in fluvial channels (Cs) in the St Bees Sandstone Formation of the eastern
1105 Irish Sea Basin (Fleswick Bay, St Bees); (g) Core plug-scale horizontal hydraulic conductivity in
1106 the channel sandstone (Cs) and overbank mudstone (Mu) of the St Bees Sandstone Formation in
1107 the eastern Irish Sea Basin (Sellafield area, Nirex, 1993b, c).

1108 **Figure 7.** Sherwood Sandstone aquifer of the eastern England Shelf (basemap from
1109 GeoMappApp). (a) Median core plug hydraulic conductivity (Allen et al., 1997; Koukis, 1978;
1110 Pokar et al., 2006) and transmissivity ranges in the Sherwood Sandstone aquifer (from Allen et
1111 al., 1997; Rivers et al., 1996); (b) Northward variation in the relative proportion of principal
1112 lithofacies characterizing the aquifer (data from BGS, 2015; Medici et al., 2015; Taylor et al.
1113 2003, West & Truss, 2006; Wakefield et al. 2015).

1114 **Figure 8.** Fluvial and aeolian facies associations and permeability as a function of subsidence
1115 rate and distance from sediment source. Middle panel shows influence of subsidence rate on
1116 mudstone preservation in fluvial channel deposits.

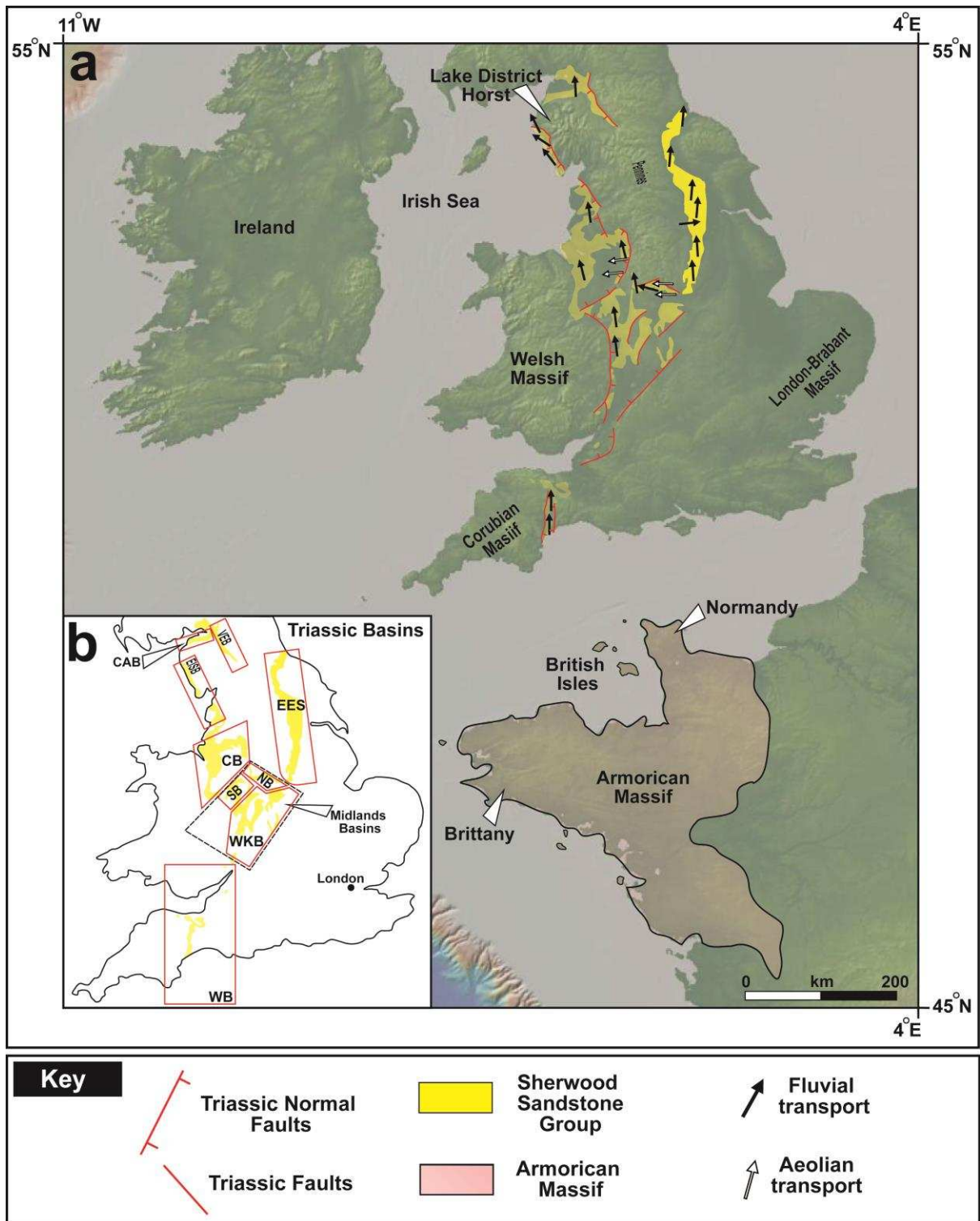


Fig. 1

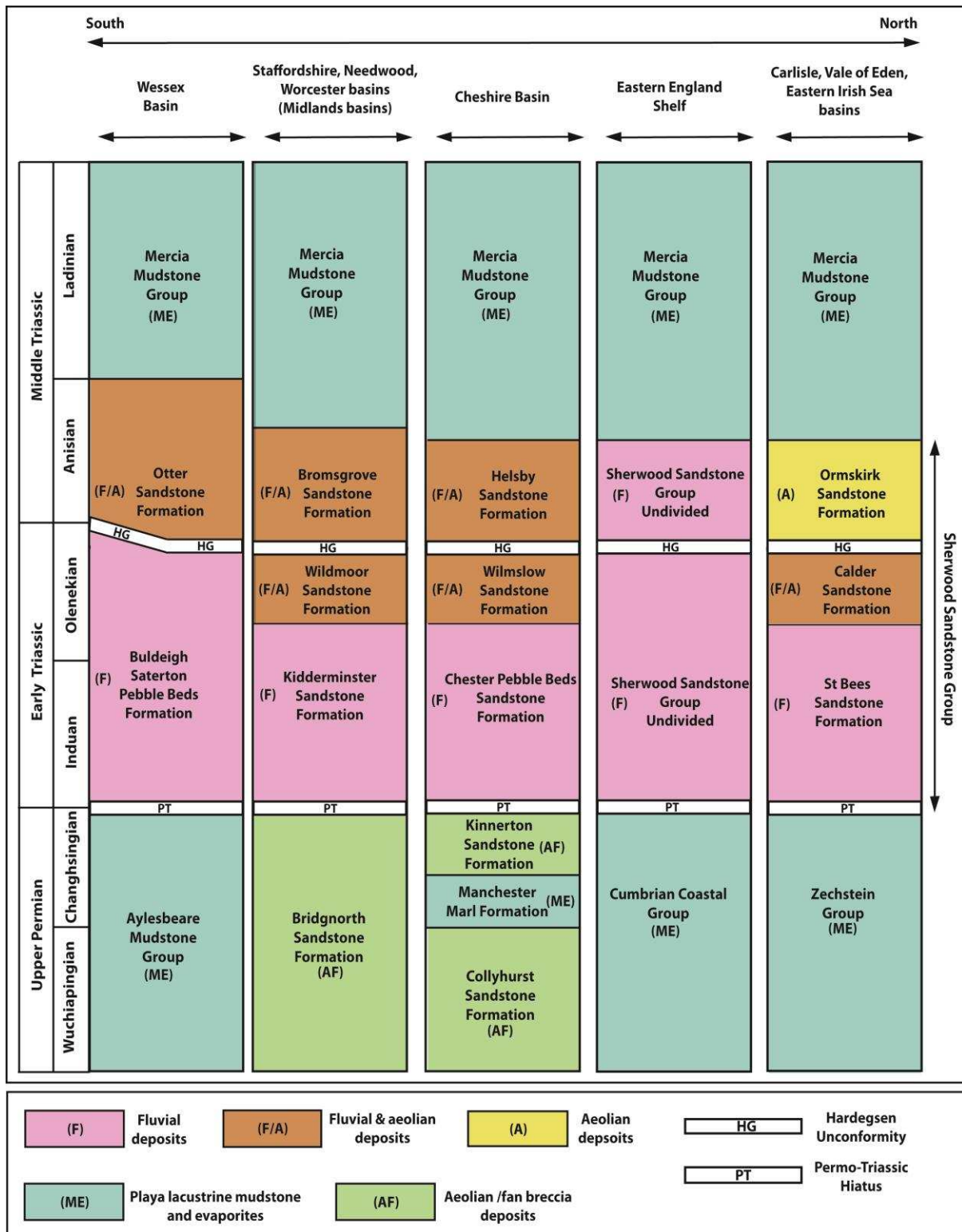


Fig. 2

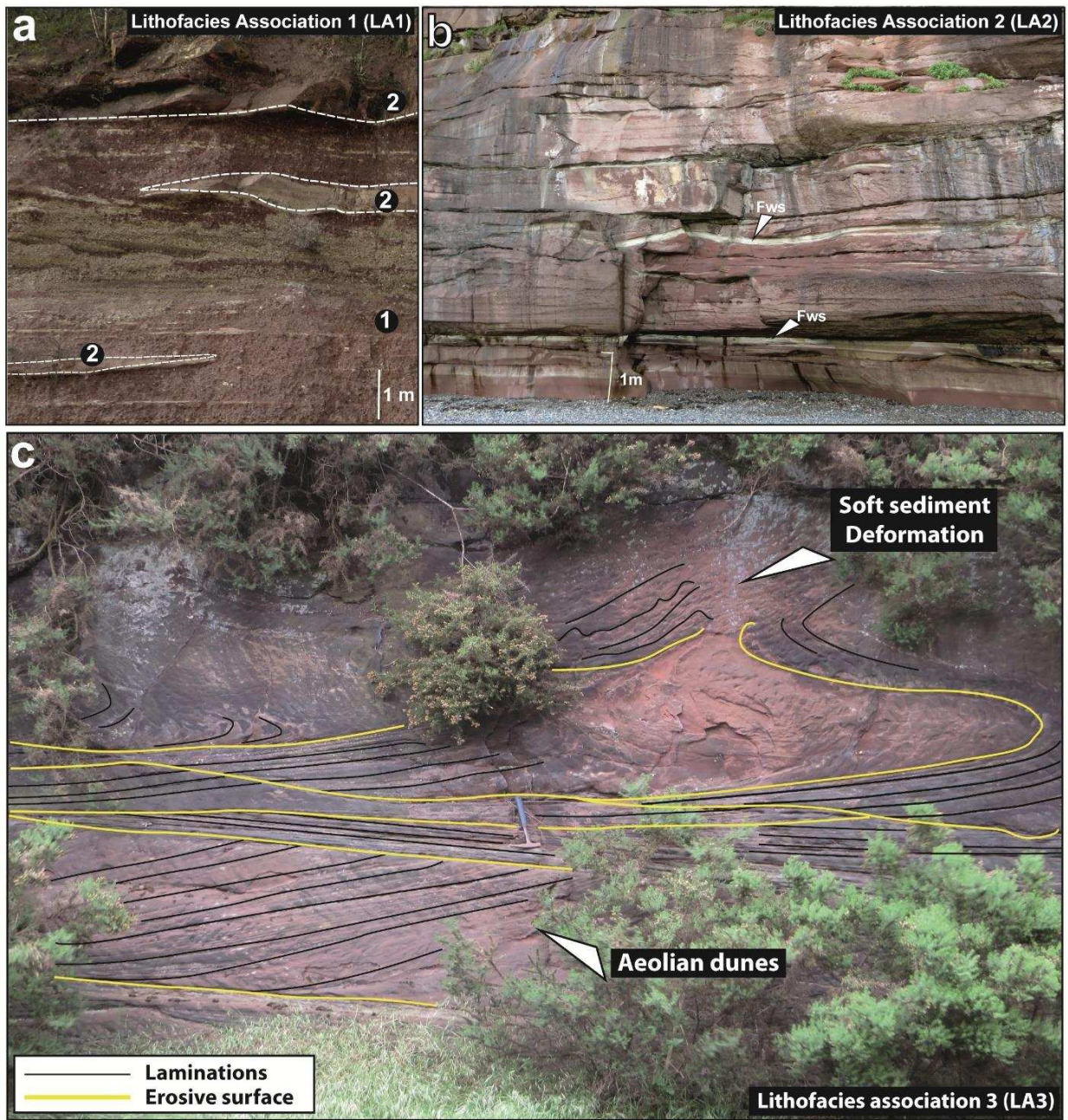


Fig. 3

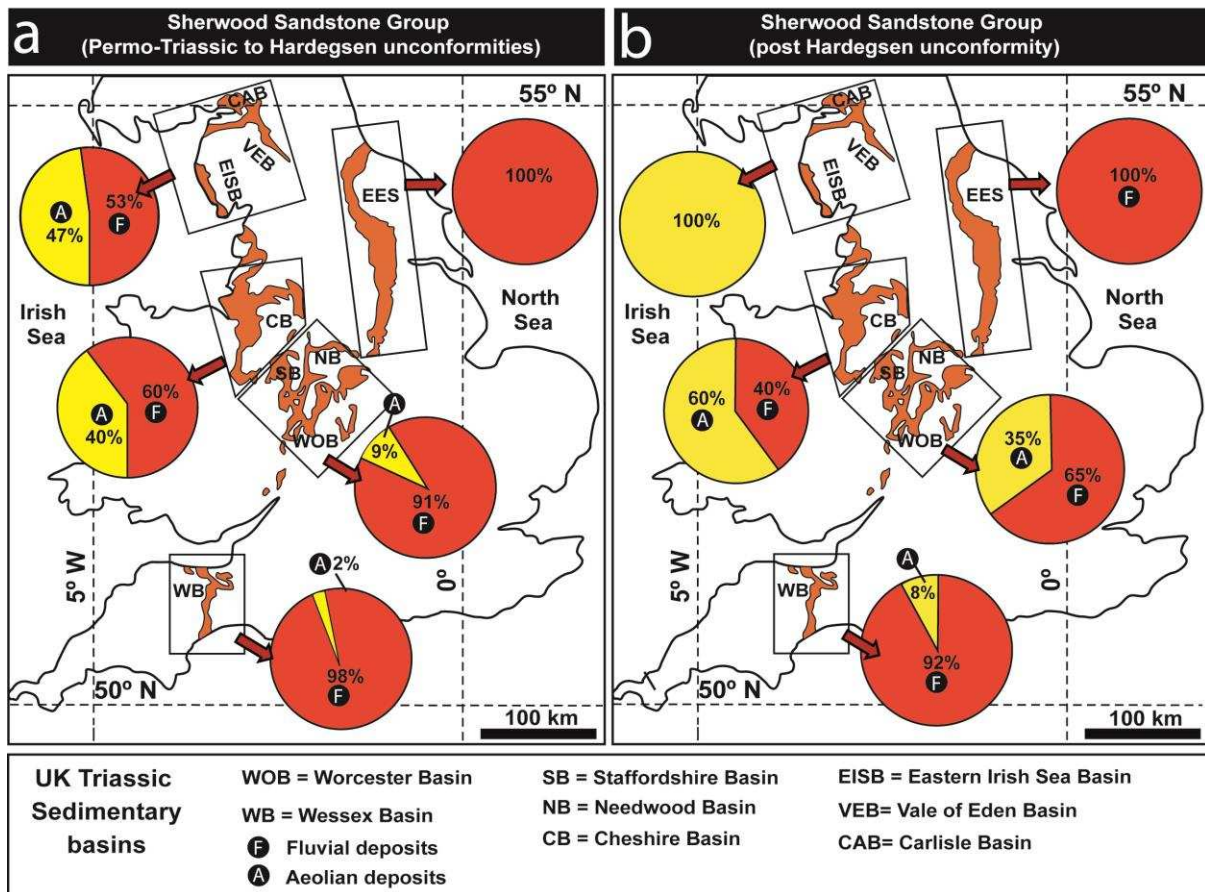


Fig. 4

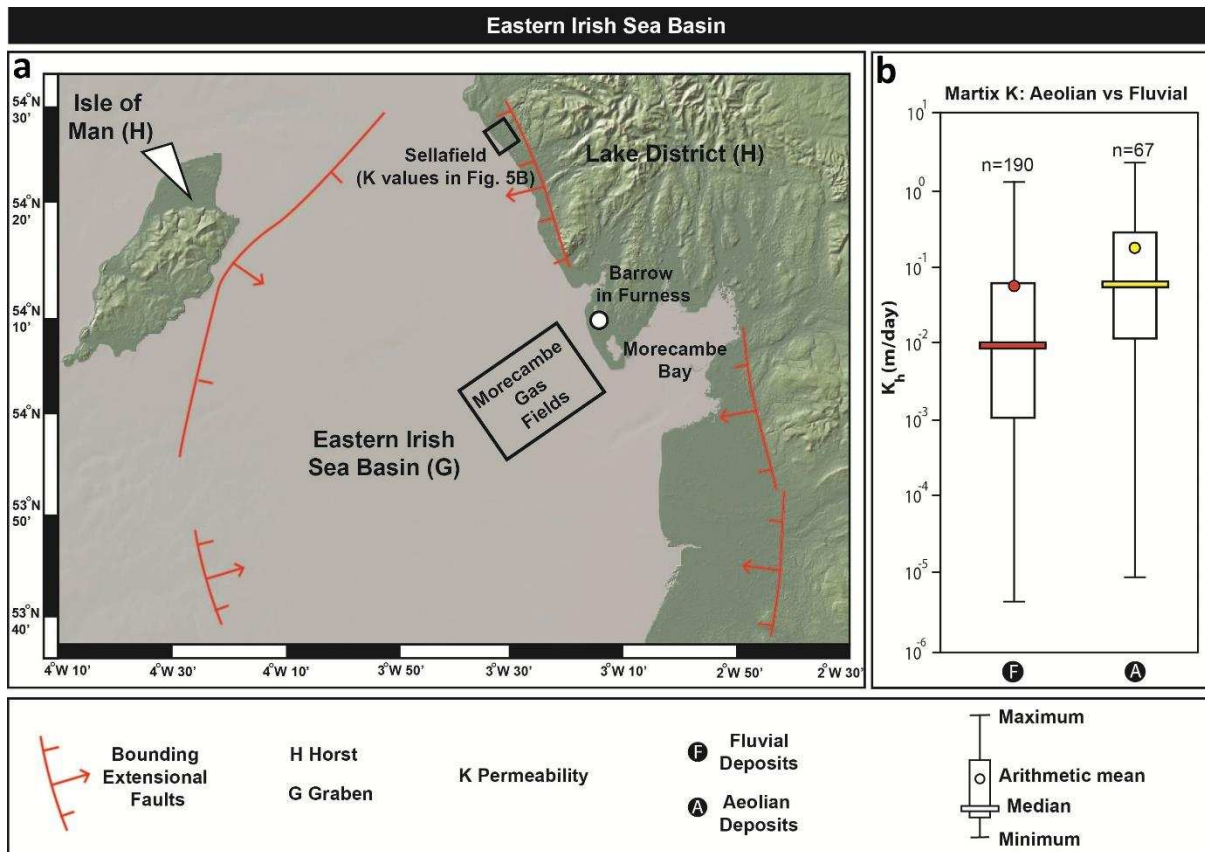
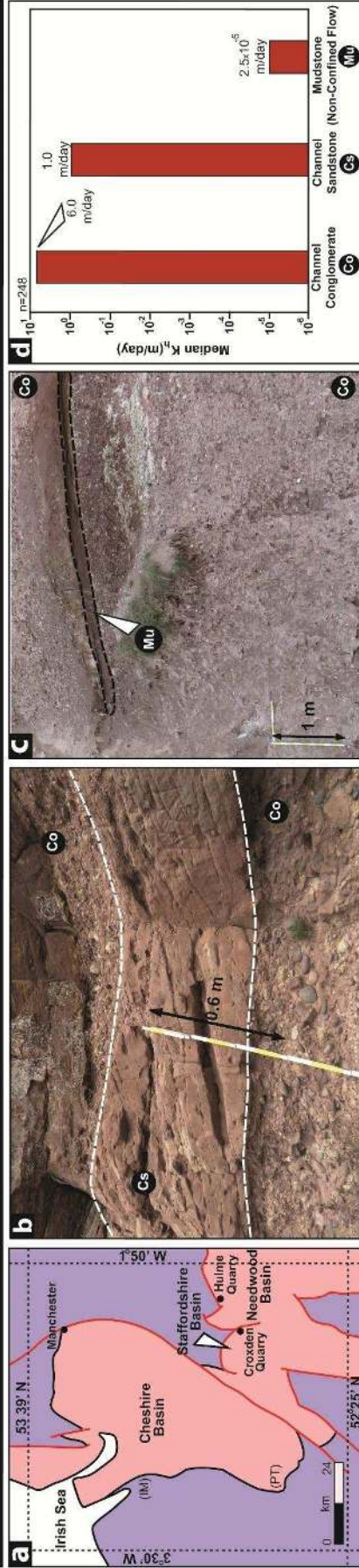


Fig. 5

Worcester, Staffordshire and Needwood Basins: Lithofacies vs. Matrix Permeability



Eastern Irish Sea Basin: Lithofacies vs. Matrix Permeability



Fig. 6

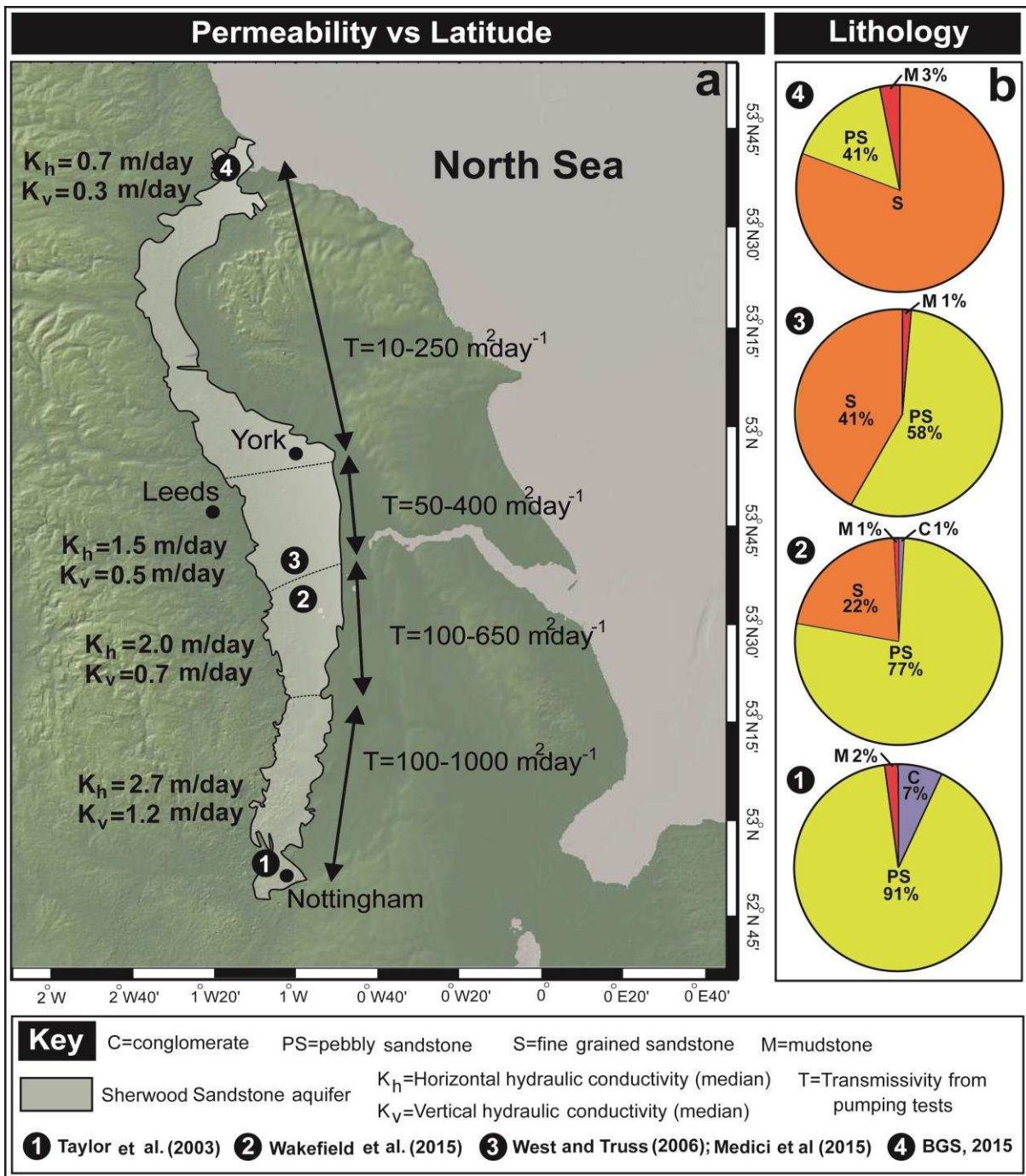


Fig. 7

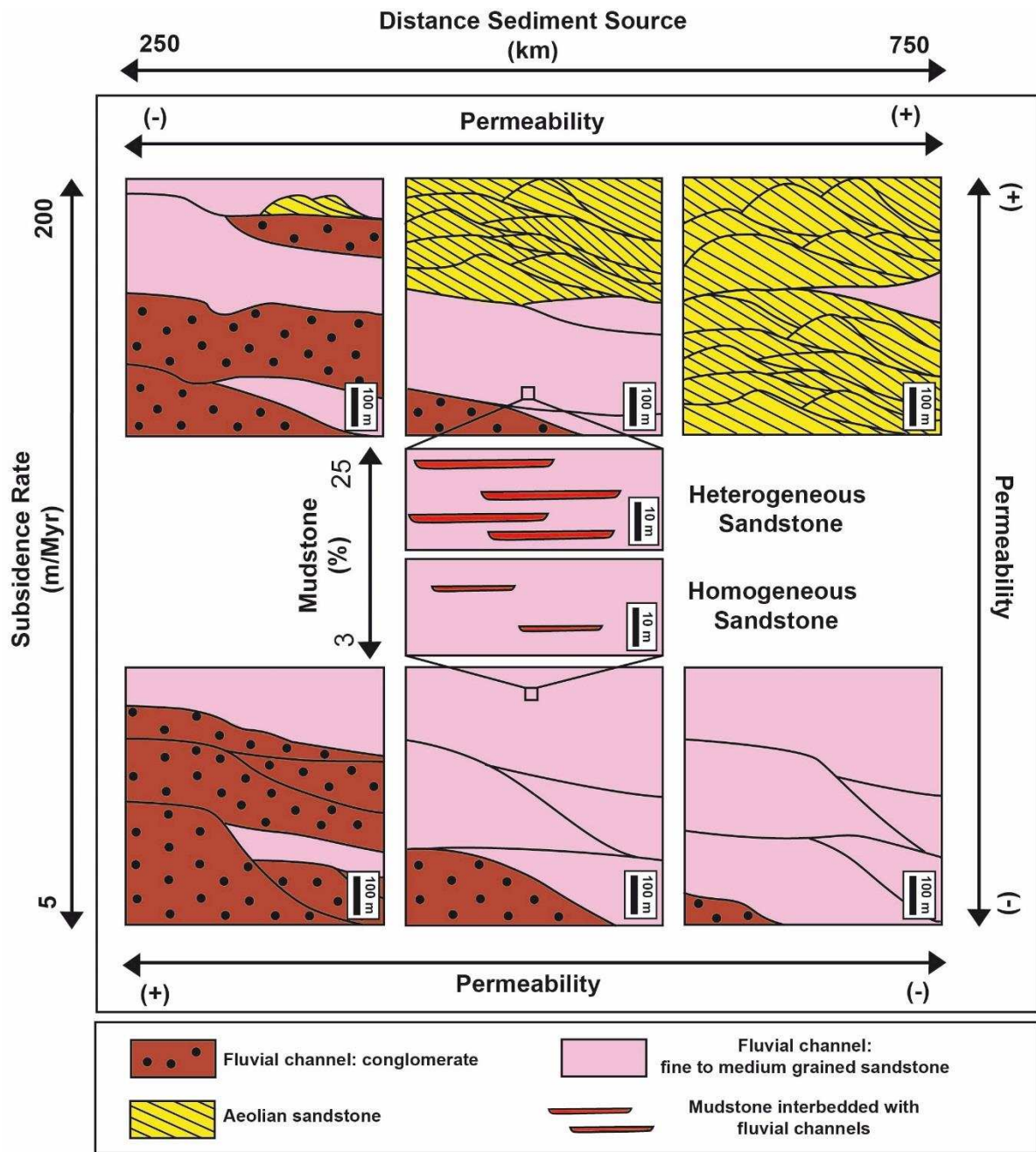


Fig. 8