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**Article:**

Steventon, MJ, Jackson, CA-L, Johnson, HD et al. (6 more authors) (2021) Evolution of a sand-rich submarine channel–lobe system, and the impact of mass-transport and transitional-flow deposits on reservoir heterogeneity: Magnus Field, Northern North Sea. *Petroleum Geoscience*, 27 (3). petgeo2020-095. ISSN 1354-0793

<https://doi.org/10.1144/petgeo2020-095>

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# 1 Evolution of a sand-rich submarine channel-lobe system and 2 impact of mass-transport and transitional flow deposits on 3 reservoir heterogeneity: Magnus Field, northern North Sea

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15 Running header: *Impact of mass-transport and transitional flow deposits on reservoir heterogeneity*

16 Conflict of interest: The authors declare no known conflicts of interest associated with this publication.

## 17 18 **ABSTRACT**

19 The geometry, distribution, and rock properties (i.e. porosity and permeability) of turbidite reservoirs,  
20 and the processes associated with turbidity current deposition, are relatively well known. However, less  
21 attention has been given to the equivalent properties resulting from laminar sediment gravity-flow  
22 deposition, with most research limited to cogenetic turbidite-debrites (i.e. transitional flow deposits) or  
23 subsurface studies that focus predominantly on seismic-scale mass-transport deposits (MTDs). Thus,  
24 we have a limited understanding of the ability of sub-seismic MTDs to act as hydraulic seals and their  
25 effect on hydrocarbon production, and/or carbon storage. We investigate the gap between seismically  
26 resolvable and sub-seismic MTDs, and transitional flow deposits on long-term reservoir performance  
27 in this analysis of a small (<10 km radius submarine fan system), Late Jurassic, sandstone-rich stacked  
28 turbidite reservoir (Magnus Field, northern North Sea). We use core, petrophysical logs, pore fluid  
29 pressure, quantitative evaluation of minerals by scanning electron microscopy (QEMSCAN), and 3D  
30 seismic-reflection datasets to quantify the type and distribution of sedimentary facies and rock  
31 properties. Our analysis is supported by a relatively long (c. 37 years) and well-documented production  
32 history. We recognise a range of sediment gravity deposits: (i) thick-/thin- bedded, structureless and  
33 structured turbidite sandstone, constituting the primary productive reservoir facies (c. porosity = 22%,  
34 permeability = 500 mD), (ii) a range of transitional flow deposits, and (iii) heterogeneous mud-rich

35 sandstones interpreted as debrites (c. porosity = <10%, volume of clay = 35%, up to 18 m thick). Results  
36 from this study show that over the production timescale of the Magnus Field, debrites act as barriers,  
37 compartmentalising the reservoir into two parts (upper and lower reservoir), and transitional flow  
38 deposits act as baffles, impacting sweep efficiency during production. Prediction of the rock properties  
39 of laminar and transitional flow deposits, and their effect on reservoir distribution, has important  
40 implications for: (i) exploration play concepts, particularly in predicting the seal potential of MTDs, (ii)  
41 pore pressure prediction within turbidite reservoirs, and (iii) the impact of transitional flow deposits on  
42 reservoir quality and sweep efficiency.

43

44 *Keywords: deep-water fan/lobe, mass-transport complex (MTC), hybrid event beds (HEBs), banded*  
45 *sandstones, subsurface fluid flow, reservoir characterisation, reservoir quality, QEMSCAN.*

46

47 Sand-rich submarine fans are small- to moderate-sized systems (c. 5-100 km radius), typically fed by  
48 point-source feeder systems and/or shelf failure. By definition, such fans are characterised by a high  
49 percentage (c. >70%) of sand-grade material (e.g. Mutti & Normark 1987; Reading & Richards 1994;  
50 Mattern 2005). Sand-rich channel-lobe systems form high-quality reservoirs in many basins (e.g. the  
51 North Sea, Gulf of Mexico, Atlantic Passive Margins), and the stratigraphic architecture of their  
52 turbidite deposits have been extensively studied (e.g. Piper & Normark 1983; Reading & Richards 1994;  
53 Kendrick 1998; Prather 2003). An understanding of inter- and intra-reservoir heterogeneities within  
54 these systems is critical for reservoir evaluation (e.g. Garland et al. 1999; Drinkwater & Pickering 2001;  
55 Hodgson 2009). In this study, we document sub-seismic mass-transport deposits (MTDs) and  
56 transitional flow deposits (i.e. hybrid, banded, and “slurry” beds), highlighting their impact on  
57 hydrocarbon fluid flow and the stratigraphic evolution of a sand-rich fan.

58

### 59 **MTDs and petroleum systems**

60

61 MTDs are the product of creep, slide, slump, and debris flow processes (see Dott 1963; Nardin 1979;  
62 Coleman & Prior 1988; Weimer 1989). MTDs are typically sourced from slope or shelf-edge  
63 environments when the component of downslope shear stress exceeds the shear strength of the *in-situ*  
64 sediment (Hampton et al 1996). MTDs can be composed of a mixture of debrites and deformed  
65 sediments, derived from a failing slope or from substrate entrainment during emplacement (e.g.  
66 Pickering & Corregidor 2005; Flint et al. 2007; Tripsanas et al. 2008). The geometry, aerial extent, and  
67 thickness of MTDs is highly variable, ranging from <10 m thick (e.g. Auchter et al. 2016) to >100 m  
68 thick (e.g. Moscardelli et al. 2006). Here, we make a distinction between (1) *small-scale MTDs* resulting  
69 from single failure episodes and typically <10 m thick (hence usually sub-seismic, but covering most  
70 core, well-log and outcrop scales), and (2) *large-scale mass-transport complexes (MTCs)* comprising  
71 multiple, genetically related mass-transport and sediment gravity flow deposits, usually 10s-100s m  
72 thick (hence within seismic resolution), and often identified as a single seismic-stratigraphic unit  
73 (Weimer 1989; Beaubouef & Friedmann 2000; Ortiz-Karpf et al. 2016).

74 In petroleum systems, MTDs can act as seals (e.g. Day-Stirrat et al. 2013; Cardona et al. 2016) and less  
75 commonly as reservoirs (e.g. Jennette et al. 2000; Welbon et al. 2007; Meckel 2011). MTDs can form  
76 seals through shear deformation along a basal shear zone (BSZ), resulting in alignment of clay fabrics  
77 and increasing bulk rock density, thereby significantly reducing permeability (Dugan 2012; Day-Stirrat  
78 et al. 2013; Wu et al. 2019). Alternatively, they can act as conventional fine-grained seals with high  
79 capillary entry pressures (Downey 1984). Fluid migration can be focused along the BSZ (e.g. Sun et al.  
80 2017), or they can form fluid bypass conduits (e.g. Gamboa & Alves 2015; Sun & Alves 2020). MTDs  
81 are also linked to zones of anomalously high fluid pressures, due to either shallow overpressure

82 generated by rapid sedimentation, or shallow gas accumulations where MTDs act as capillary seals  
83 (Osborne & Swarbrick 1997). The irregular top surface relief of large MTDs can influence the  
84 behaviour of subsequent sediment gravity flows and therefore, the distribution and geometry of  
85 overlying turbidite reservoirs that in some cases may form stratigraphic traps (e.g. Armitage et al. 2009;  
86 Jackson & Johnson 2009; Dykstra et al. 2011; Ortiz-Karppf et al. 2015; Kneller et al. 2016; Bell et al.  
87 2018, Fig. 1a, b). Most work has focused on seismic-scale, sealing-MTDs, with only limited  
88 consideration given to the spatial variability of their rock properties (see Yamamoto & Sawyer 2012).  
89 Many studies use well data from shallowly buried (<1 km) MTDs, with a focus on the Gulf of Mexico  
90 (e.g. Flemings et al. 2008; Dugan 2012; Sawyer et al. 2012; Day-Stirrat et al. 2013; Wu et al. 2019).  
91 These types of studies are useful when considering the controls and location of shallow fluid flow within  
92 basins, or when analysing the failure mechanisms of submarine slopes; however, they are less relevant  
93 to understanding how MTDs may act as hydrocarbon seals, barriers, and baffles within deeply buried  
94 reservoirs. Here, we focus on MTDs that act as intra-reservoir seals, either in the form of barriers to  
95 fluid flow, forming separate reservoir compartments (e.g. Beaubouef & Abreu 2010; Algar et al. 2011),  
96 or as more localised baffles in conjunction with transitional flow deposits (e.g. hybrid beds). We  
97 ultimately show how MTDs and transitional flow deposits contribute to reservoir heterogeneity and an  
98 overall reduction in effective permeability (e.g. O'Connor & Walker 1993; Garland et al. 1999;  
99 McCaffrey & Kneller 2001; Haughton et al. 2003).

100

## 101 **Seal evaluation and MTDs**

102

103 Any evaluation of seal potential needs to focus on three properties: (i) *capacity*, which is related to  
104 minimum capillary entry pressure and controlled by pore-throat characteristics, most notably size and  
105 connectivity, (ii) *integrity*, which is related to rock ductility and tendency to fracture during  
106 deformation, and (iii) *geometry*, which is related to thickness, form, and aerial extent of the unit, and is  
107 controlled by depositional environment (Downey 1984; Kaldi & Atkinson 1997). Evidence that MTDs  
108 can act as seals is observed at several scales. Seismic-scale sealing MTDs are evident where gas-related  
109 bright spots are located directly beneath MTDs (e.g. Berndt et al. 2003; Bünz et al. 2003; Berndt et al.  
110 2012; Sun et al. 2017), and where there is a lack of gas-escape structures (e.g. pockmarks) directly  
111 above these deposits (e.g. Sarkar et al. 2012; Riboulot et al. 2013). However, seismic studies focusing  
112 on structural fabrics surrounding large (~0.5-5 km wide) rafted blocks suggest these feature may  
113 decrease seal integrity (Alves et al. 2014; Gamboa & Alves 2015; Steventon et al. 2019). Second, at the  
114 borehole-scale, analysis of petrophysical well-logs, pore fluid pressure, shear deformation, and capillary  
115 pressures characteristics all point to MTDs having relatively low permeability (Flemings et al. 2008;  
116 Dugan 2012; Yamamoto & Sawyer 2012; Day-Stirrat et al. 2013; Cardona et al. 2016; Wu et al. 2019)  
117 (Fig. 1c).

118

## 119 **Reservoir evaluation and transitional flow deposits**

120

121 In relation to reservoir evaluation, small-scale MTDs, thin-bedded turbidites, and transitional flow  
122 deposits (e.g. linked turbidite-debrite beds, hybrid beds, and banded beds; see Lowe & Guy 2000;  
123 Haughton et al. 2003; Talling et al. 2004) can impart significant heterogeneity within otherwise high-  
124 quality turbidite reservoirs. This type of bed-scale heterogeneity is often below seismic and sometimes  
125 conventional well-log scales (i.e. cm-dm-scale) and requires image log or core data for effective  
126 analysis. Thin-bedded turbidites or simply “*thin beds*”, typically associated with submarine levee, lobe  
127 fringe, and basinfloor settings, or sediment bypass-dominated zones (Stevenson et al. 2015), have  
128 received much attention in both outcrop (e.g. Mutti 1977; Stow & Piper 1984; Walker 1985) and the  
129 subsurface (e.g. Kendrick 1998; Kendrick 2000; Hansen et al. 2017). Thin-beds can contribute  
130 significantly to reservoir pay where they are separated by thin mudstones; in other cases they can be  
131 mudstone-dominated and act as baffles (Passey et al. 2006). However, considerably less attention has  
132 been given to the role of transitional flow deposits (see Haughton et al. 2003; Lowe et al. 2003; Talling  
133 et al. 2004). Analysis of transitional flow deposits has focused on their distribution in relation to an  
134 idealised lobe complex (e.g. Hodgson 2009; Fonnesu et al. 2015; Sychala et al. 2017b) and their  
135 occurrence in confined basins (e.g. Haughton et al. 2009; Fonnesu et al. 2018; Soutter et al. 2019).  
136 Studies of transitional flow deposit reservoir quality and their impact on subsurface fluid flow are rarer  
137 (see Amy et al. 2009; Porten et al. 2016; Southern et al. 2017).

138

## 139 **Aims and significance**

140

141 Here, we aim to bridge the gap between the potential production impact of shallowly-buried  
142 seismically-resolvable MTDs and deeply-buried sub-seismic MTDs and transitional flow deposits, by  
143 studying their distribution within an Upper Jurassic turbidite sandstone reservoir in the Magnus Field,  
144 northern North Sea (Fig. 2). The Magnus Field is a mature oilfield: discovered in 1974, with first oil  
145 production in 1983, and the start of enhanced oil recovery in 2002 (MacGregor et al. 2005). There is an  
146 estimated c.1.8 billion barrels of STOIP, with a predicted recovery factor of 50-55% (Shepherd et al.  
147 1990; MacGregor et al. 2005). We use the comprehensive well-bore and seismic reflection dataset to  
148 conduct a thorough analysis of the reservoir’s nature, origin, and distribution of physical properties (i.e.  
149 porosity, permeability, volume of clay, density/compressional velocity), highlighting the role of sub-  
150 seismic MTDs and transitional flow deposits. We focus on three main aims: (i) to capture the  
151 stratigraphic evolution of the submarine slope depositional system in the Magnus reservoir, (ii) to  
152 characterise the lateral variability of sub-seismic MTDs and assess their impact on fluid flow, and (iii)

153 to investigate the impact of overlying transitional flow deposits on reservoir quality and fluid flow. Our  
154 study has implications for petroleum exploration and production, and the role of MTDs in carbon  
155 storage projects, including predicting the distribution of deep-water reservoir-seal pairs, and  
156 understanding the impact of heterogeneities on turbidite reservoir connectivity, compartmentalisation,  
157 and pore-pressure prediction.

158

## 159 **BASIN SETTING & STRATIGRAPHY**

160

### 161 **Structure**

162 The Viking Graben represents one arm of the northern North Sea trilete rift system, formed through  
163 multiple episodes of extension during the Permo-Triassic and latest Jurassic-Early Cretaceous (e.g.  
164 Badley et al. 1984; Badley et al. 1988; Yielding 1990). The East Shetland Basin comprises several half-  
165 grabens, bound to the east by the Viking Graben and to the west by the Shetland Platform, Unst Basin,  
166 and Magnus Basin (Johns & Andrews 1985; Lee & Hwang 1993). The basin has undergone a complex  
167 tectono-stratigraphic history, influenced by: (i) Caledonian basement structural grains, (ii) Middle-to-  
168 Late Jurassic and Early Cretaceous rifting, associated with the formation of the Viking Graben, and (iii)  
169 early Cretaceous rifting and opening of the Magnus and Møre Basins in the North Atlantic (Shepherd  
170 1991; Gabrielsen et al. 1999; Al-Abry 2002). The post-Triassic sedimentary succession of the East  
171 Shetland Basin consists of Triassic-Jurassic tilted fault blocks, with syn-rift sedimentation transitioning  
172 from shallow marine to deep marine environments (Partington et al. 1993; Morris et al. 1999). The  
173 succession can be split into: (i) the Lower Jurassic post-rift shallow marine Dunlin Group (Jurassic  
174 sequence (J) 10), (ii) the Middle Jurassic post-rift deltaic Brent Group (J20-30), which included a period  
175 of minor fault activity recorded by a top-Rannoch unconformity, (iii) the initiation of Late Jurassic  
176 rifting during deposition of the Tarbert Formation, and (iv) deposition of the Upper Jurassic syn-rift  
177 shelfal Heather (J30-40) and deep-marine Kimmeridge Clay Formations (J60-70) (Partington et al.  
178 1993; Morris et al. 1999; Dominguez 2007) (Fig. 2, 3, X-X<sup>1</sup>). These deposits were subsequently  
179 truncated during the formation of the Base Cretaceous unconformity (BCU) (Dominguez 2007). During  
180 the Cretaceous and Cenozoic, the East Shetland Basin underwent post-rift thermal subsidence, and a  
181 ~3.5 km-thick marine succession was deposited in the Magnus area (Partington et al. 1993; Ravnås &  
182 Steel 1997).

183 The Magnus Field is located on the north-western limit of the East Shetland Basin, within the Penguin  
184 half-graben, bound to the north-west by the Magnus and End of the World faults (Shepherd 1991;  
185 Thomas & Coward 1995) (see inset maps, Fig. 2). The field lies on the crest of a tilted fault block in  
186 the footwall of the Magnus Fault, with hydrocarbons trapped by a combination of stratigraphic pinch-

187 out and truncation below the BCU (Shepherd 1991) (Fig. 3a, b). In the Magnus area, Jurassic to  
188 Cretaceous rifting led to the development of: (i) NNW-SSE and N-S-striking arrays of Late Bathonian  
189 early syn-rift faults, offsetting the Brent Group (pre-rift) and active during deposition of the Heather  
190 Formation, (ii) a WNW-ESE-striking array of late syn-rift faults predominantly in the Heather and  
191 Lower Kimmeridge Clay Formations, and later reactivation of the NNW-SSE-striking array of faults,  
192 and (iii) NE-SW Atlantic rifting trend in the Early Cretaceous (Fig. 3c, d) (see Al-Abry 2002). Major  
193 structures in the Magnus area include: the Brent, Magnus, and the End of the World Faults. The Brent  
194 Fault trends NNW-SSE through the Magnus area, with both the Heather and Kimmeridge Clay  
195 formations thickening into the hanging-wall of the fault, especially in the southern area of the field (Fig.  
196 3b, c). The Magnus Fault strikes NE-SW to N-S, dipping to the NW, and contains a fault scarp  
197 degradation complex in its footwall (e.g. Underhill et al. 1997). The End of the World Fault strikes NE-  
198 SW and dips to the NW, bounding the northern area of the Penguin half-graben (Al-Abry 2002) (Fig.  
199 2, inset maps).

200

## 201 **Magnus Field Reservoir Stratigraphy**

202

203 The Magnus Field reservoir is contained within the Upper Jurassic Kimmeridge Clay Formation,  
204 comprising (bottom to top) (Fig. 2): (i) the Lower Kimmeridge Clay Formation (J50-62) composed of  
205 a turbidite and clastic injectite system (see Goodall et al. 1999), (ii) the Magnus Sandstone Member  
206 (MSM, J63-64), composed of a sand-rich turbidite system, and (iii) the Upper Kimmeridge Clay  
207 Formation (J66-70), composed of hemipelagic mudstones (Partington et al. 1993; Morris et al. 1999;  
208 Fraser et al. 2002) (Fig. 2, 3b). The MSM (the focus of this study) comprises (bottom to top) (Fig. 3e):  
209 (i) the lower MSM reservoir (MSA), (ii) a basin-wide mud-rich unit, MSB, which is related to  
210 *Autissiodorensis* maximum flooding surface, (iii) the upper MSM reservoir, which can be subdivided  
211 into sand-rich (MSC, MSE, MSG) and mud-rich (MSD, MSF) units (MSF is marked by *Iathetica re-*  
212 *influx*), and (iv) a transition into the Upper Kimmeridge Clay Formation (MSG-MSH), marked by the  
213 *Hudlestoni* maximum flooding surface (Partington et al. 1993; Morris et al. 1999). Two main  
214 depositional trends are observed: (i) a lower reservoir trend (MSA) deposited within a centrally fault-  
215 controlled depocentre, and (ii) an upper reservoir trend (MSC-H) with a southern depocentre in the  
216 footwall of the Brent Fault, and a northern depocentre overlapping the Brent Fault footwall high (Fig. 2)  
217 (Ravnås & Steel 1997; Morris et al. 1999; Al-Abry 2002).

218

## 219 **DATA & METHODS**

220

221 We use a 3D seismic-reflection survey and 83 wells, containing petrophysical well-logs,  
222 biostratigraphic tops, and fluid pore pressure data (see Supplementary Material). This included 33 wells  
223 with core photos, of which five were available for physical core logging (see Fig. 2a for locations).

224

### 225 **Core and wireline petrophysics**

226 Detailed sedimentological core logging (1:10 scale, i.e. 1 m = 10 cm) of the MSB and surrounding  
227 lower (MSA) and upper (MSC) MSM reservoir units was undertaken on five wells, covering a  
228 combined stratigraphic thickness of 238.5 m (see Fig. 2 for well locations). Data collection comprised  
229 lithology, grain-size, bed thickness, type of bed contacts, and primary sedimentary structures and  
230 (secondary) soft sediment deformational structures. QEMSCAN<sup>®</sup> (quantitative evaluation of minerals  
231 by scanning electron microscopy) was used to quantify the grain size and shape, textural information,  
232 mineralogy, and porosity distribution for 14 core samples from well 211/12a-M16, located in the central  
233 area of the field (Fig. 2a). The QEMSCAN platform is a scanning electron microscope (SEM) with  
234 energy dispersive x-ray (EDS) detectors and provides automated petrographic quantification of spatially  
235 resolved compositional and textural data. For this study, the data were collected by Rocktype Ltd using  
236 a QEMSCAN<sup>®</sup> WellSite instrument (Aspex Extreme Scanning Electron Microscope with 5030 Bruker  
237 EDS detectors) using the FieldScan mode at 15 kV beam energy and 10  $\mu\text{m}$  stepping interval. Details  
238 of the microscope set-up can be found in Supplementary Material. QEMSCAN samples (QM1 to  
239 QM14) were taken from reservoir units MSA, MSB, MSC, and MSE (see Fig. 4).

240 In addition to physical core, a full suite of wireline logs, pressure, and core analysis data were available  
241 (see Supplementary Material). Core plug measurements of porosity, horizontal permeability (Kh) and  
242 vertical permeability (Kv) were used to define flow units. Fluid pressure data (repeat formation tests)  
243 was also used to identify internal pressure breaks within the reservoir, which may reflect the presence  
244 of structural or stratigraphic barriers. Well-log-based reservoir zonation and correlation of maximum  
245 flooding surfaces to subdivide the primary Magnus reservoir units (MSA-H) was guided by  
246 biostratigraphic reports from EnQuest and BP, along with published biostratigraphic schemes (see  
247 Partington et al. 1993; Morris et al. 1999, Supplementary Material).

248

### 249 **Seismic interpretation**

250 The 3D pre-stack depth migrated seismic-reflection (ocean bottom cable) survey used in this study  
251 covers a c. 178 km<sup>2</sup> area, imaging the tilted fault block containing the Magnus Field. The data are SEG  
252 reverse polarity (i.e. European polarity, with an increase in acoustic impedance = trough), zero-phased,  
253 and have a lateral bin spacing of 12.5 $\times$ 12.5 m and a vertical resolution (assumed to be tuning thickness,  
254 1/4 of the dominant wavelength) of c. 12 m at 3 km. We interpret three seismic horizons within and

255 surrounding the Magnus reservoir: (i) the top Heather Formation (ii) the MSA/MSB boundary, and (iii)  
256 the BCU. In addition, a coloured inversion cube was available that allowed further analysis of the lateral  
257 variability of the depositional systems (for method see Lancaster & Whitcombe 2000).

258 The sand-rich reservoir sections are predominantly characterised by high-amplitude, positive (SEG-  
259 reverse polarity) reflections, related to an interface from higher-density background sediments to  
260 hydrocarbon-filled lower-density (“soft”) sands. This equates to sand-rich reservoir zones being  
261 characterised by negative acoustic impedance responses (Fig. 3a). Note that amplitude maps are only  
262 extracted up to the vertical resolution of the seismic data (c. 12 m).

263

264

## 265 **SEDIMENTOLOGY OF RESERVOIR SANDSTONE FACIES**

266

267 This core-based sedimentary facies analysis is focused on the MSA, MSB, and upper (MSC to MSH)  
268 units of the MSM reservoir (see Fig. 2, 3e). Seven facies types have been recognised: (i) thick-bedded  
269 sandstones (F1); (ii) thin-bedded sandstones (F2); (iii) banded heterolithic beds (F3); (iv) hybrid beds  
270 (F4); (v) heterogeneous deformed beds (F5); (vi) mudstones (F6); and (vii) heterogeneous argillaceous  
271 beds (F7) (see Table 1, Fig.5).

272

### 273 **Turbidite deposits**

274 *Facies 1: Thick-bedded sandstones (high-density turbidites)*

275 *Description:* Fine- to coarse-grained, 0.2-1 m-thick amalgamated sandstone beds with predominantly  
276 massive or planar laminated internal features (Fig. 5, F1). Normal grading fine sand to silt is observed  
277 at bed tops, associated with current ripple and planar laminated bed tops (see Facies 2). Intercalated  
278 mudclast-rich horizons (~0.5-2 m thick) (Fig. 5, F1) comprise angular and/or sheared clasts (<1-8 cm  
279 diameter). Intermittently preserved medium- to granule-grade sandstones (0.05-0.25 m thick), with  
280 matrix- and grain-supported intervals display erosive bases, weak normal grading, and poorly developed  
281 imbrication of quartz, lithic, and mudstone clasts (Fig. 5, F1).

282 *Interpretation:* The massive to planar laminated sandstone beds, are interpreted to have been deposited  
283 by high-density turbidity currents, with rapid deposition and bed aggradation suppressing tractional  
284 bedform development (Lowe 1982; Kneller & Branney 1995). The basal sandstones with erosive bases  
285 are interpreted to be formed by tractional processes at the base of high concentration turbidity currents,  
286 with the coarsest-grained material deposited first (e.g. Walker & Mutti 1973; Lowe 1982). Mudclast-

287 rich horizons are interpreted to represent lag deposits and represent locations dominated by sediment  
288 bypass (Stevenson et al. 2015).

289

290 *Facies 2: Thin-bedded sandstone (low-density turbidite)*

291 *Description:* Very fine- to fine-grained, c. 0.05-0.2 m-thick sandstone beds, showing normal grading,  
292 current ripple cross-lamination, including climbing sets, convolute lamination, and planar-parallel  
293 lamination (Fig. 5, 6k). Typically, sandstone bed bases are sharp and planar to weakly erosional, and  
294 bed tops may be sharp or normally graded. The sandstones can occur in either: (i) sets of thin bedded  
295 sandstones interbedded with mudstones (~3 m set thickness), or (ii) as individual sandstone beds above  
296 high-density turbidites (Facies 1).

297 *Interpretation:* The thin-bedded structured sandstones are interpreted to have been deposited by low  
298 density turbidity currents, representing ‘classical’ turbidites (mainly  $T_C/T_{D/E}$  divisions) (Bouma 1964;  
299 Mutti 1977; Talling et al. 2012). The climbing ripple sets represent periods of rapid suspended sediment  
300 fallout (Fig. 6k) (Jobe et al. 2012).

301

### 302 **Transitional flow deposits**

303 *Facies 3: Banded beds*

304 *Description:* This facies is dominated by 5-35 cm-thick sandstones beds that comprise alternating dark  
305 and light, cm-scale, parallel to sub-parallel bands (Fig. 5, F3). The light bands can be planar and current  
306 ripple cross laminated and are sand-rich. Dark bands have elevated amounts of mud, and are less well  
307 sorted, but with similar maximum grain-size to the light bands (Fig. 5, F3). The upper contacts of banded  
308 beds record a sharp grain size break into an overlying mudstone.

309 *Interpretation:* Banded turbidite sandstone beds and bed divisions have been reported in the North Sea  
310 (e.g. Lowe & Guy 2000; Haughton et al. 2009; Stevenson et al. 2020), however, the process of  
311 deposition is still under debate. Lowe & Guy (2000) proposed a model of cyclic freezing of a near-bed  
312 plug flow, and postulate that banding forms between turbulent and laminar flow states, through  
313 variations in near-bed clay content modifying flow cohesion from low (sands-silt bands) to high (clay-  
314 rich bands). However, flume tank experiments suggest flows with migrating bedforms within the upper  
315 stage plane bed flow regime can also produce banded beds (see Baas et al. 2011; Baas et al. 2016).  
316 Stevenson et al. (2020) provide a thorough review of banded turbidite sandstones, and supports the Baas  
317 model for banded sandstones of the scale observed here.

318

319 *Facies 4: Structured argillaceous sandstones (hybrid beds)*

320 *Description:* This facies comprises of approximately 15-40 cm thick bipartite beds with lower fine- to  
321 medium-grained sandstone divisions, and upper argillaceous sandstone division (Fig. 5, F4). The  
322 lowermost sandstones are well-sorted and appear as either: (i) normally graded to ungraded sandstones,  
323 with basal loading structures and sheared mudstone clasts at the base, dewatering pipes, and  
324 mudclasts/chips concentrated at the top or (ii) weakly laminated to banded sandstones (Facies 3) with  
325 sharp to slightly wavy bases. The overlying argillaceous sandstone division often has a sharp, loaded  
326 or variably deformed contact, sometimes with sand injection, and can contain outsized granules, highly  
327 sheared mudstones clasts, and dispersed quartz grains forming a ‘starry night’ appearance (Fig. 5). A  
328 sharp contact usually marks the base of thin (mm-cm-scale) parallel laminated to current ripple cross-  
329 laminated sandstones, followed by a thin mudstone cap.

330 *Interpretation:* Beds comprising lower sandstone divisions overlain by argillaceous sandstones are  
331 interpreted as turbidites with linked debrites (sensu Haughton et al. 2003), whereby the lower division  
332 represents a sandy turbidite and the upper argillaceous division a muddy debrite (Haughton et al. 2003;  
333 Talling et al. 2004). Overlying graded beds might represent low-density turbulent flow/wake deposits  
334 (Haughton et al. 2009). The beds conform well with Haughton et al. (2009) five part classification  
335 scheme (H1-5), albeit sometimes lacking rippled sandstones and mudstone caps. Hybrid beds may be  
336 attributed to sediment gravity flow transformation (Fisher 1983), with flow concentration increasing  
337 with runout distance of a turbidity current related to entrainment of substrate, or the partial  
338 transformation of an initial debris flow (e.g. Haughton et al. 2003; Sumner et al. 2009; Hodgson 2009;  
339 Fonnesu et al. 2015; Kane et al. 2017).

340

341 *Facies 5: Deformed-remobilised “slurry” beds*

342 *Description:* This facies comprises beds of fine-grained, light-grey sandstones and siltstones, and dark-  
343 grey mud-rich sandstones. Individual beds are 0.25-0.7 m thick, with irregular basal contacts (Fig. 5,  
344 F5). The heterolithic alternations display soft sediment deformation, including ball and pillow  
345 structures, folded and sheared fabrics, and sheared/injected mudstone horizons (Fig. 5, F5). The beds  
346 show a similar trend to the hybrid beds, with a lower cleaner sandstone division overlain by a more  
347 argillaceous division. The beds are commonly associated with banded beds (Facies 3). However, these  
348 “slurry” beds are different to hybrid beds (Facies 4) because they show: (i) gradational changes between  
349 sand- and mud-rich facies with poorly developed debritic textures, and (ii) may be chaotic or  
350 unstructured.

351 *Interpretation:* The chaotic sheared nature of the beds and syn-sedimentary soft sediment deformation  
352 structures suggest downslope movement of a heterolithic unit that was partially liquefied. The common

353 occurrence above or below banded beds suggested a link between Facies 3 and 5. Therefore, we  
354 interpret the facies to represent remobilised banded sandstone beds which were transported farther  
355 downslope. This facies is similar to the “mixed slurry flows” described from the Britannia Field (Lowe  
356 & Guy 2000), where the facies are interpreted to be deposited initially as banded beds, which were later  
357 remobilised as water-rich heterolithic mixtures (Barker et al. 2008; Eggenhuisen et al. 2010).

358

### 359 **Mudstone deposits**

#### 360 *Facies 6: Mudstones*

361 *Description:* Massive to parallel laminated (mm-scale) mudstones and siltstone beds, with sharp  
362 contacts and normal grading profiles (based on colour change). Bed thicknesses are variable (from 0.2-  
363 >1 cm).

364 *Interpretation:* We interpret that these mudstones were deposited by either: (i) suspension settling of  
365 very fine-grained, pelagic and hemipelagic sediments in a very low-energy environment; and/or (ii)  
366 from mud-rich dilute turbidity currents (Stow & Shanmugam 1980; Boulesteix et al. 2019).

367

368

## 369 **SEDIMENTOLOGY OF MTD FACIES**

370

### 371 **Overview of the MSB unit (Facies 7)**

372 Facies 7 forms a 1-18 m-thick unit that constitutes the entirety of the MSB unit (Fig. 4b, 7a). Three sub-  
373 facies are recognised, based on varying clay concentrations: (i) light-coloured and sand-rich  
374 (VSH<25%, D1); (ii) grey to dark-grey coloured and mud-rich (VSH 25-50%, D2-D4), and (iii)  
375 brecciated (D5) (see Table 2). We here describe these units in details, along with nature of their  
376 bounding surface and the overall lateral variability within the MSB, before interpreting the formative  
377 physical processes and environment.

378

### 379 **Sub-facies types**

380

#### 381 *Sub-facies D1 (sand-rich debrites)*

382 *Description:* Light-grey muddy sandstones, predominantly composed of fine to very coarse grained  
383 sand, with both clast- (Fig. 7c) and matrix-supported (Fig. 6a) areas. Clast are mudstone and sandstone,

384 and sub-rounded to angular, with sheared and/or squeezed fabrics (Fig. 6a). Intact clasts of bedded  
385 sediments are smaller than Facies D2-4 (<60 cm) and composed of mudstones with only minor  
386 disaggregation of original bedding (Fig. 7c).

387

388 *Sub-facies D2-4 (mud-rich debrites)*

389 *Description:* Matrix-supported sandy mudstone with “floating” grains (fine to coarse sand grade). The  
390 colour of the poorly sorted matrix varies from grey (D2-3, VSH=25-50%) to dark grey (D4,  
391 VSH=>50%) with increased clay content (Fig. 6b-d). A ‘starry night’ matrix texture is composed of  
392 predominantly granule to pebble-grade clasts of quartz, mudstones, belemnites and carbonaceous  
393 material, supported within the mudstone matrix (Fig. 5, D2-4, Fig. 6b-d). Belemnites are commonly  
394 found near the base of MSB (Fig. 7b, d). Small clasts (<7 cm diameter) within the matrix are  
395 predominantly dark mudstones, which are either sub-rounded to angular, or sheared and aligned parallel  
396 to bedding (Fig. 4b, 6b, 7, D2-4,). Larger intact bedded and disaggregated clasts (up to 1.5 m thick) are  
397 observed throughout the unit (Fig. 7c, g), which are locally overturned (including Facies 1, 2, 3 and 6).  
398 Some of the larger clasts are composed of clean sandstones with angular edges (e.g. top of Fig. 7g) that  
399 are not oil stained, while others display sheared/squeezed fabrics and soft-sediment deformation (e.g.  
400 Fig. 7f). The clasts can be distinguished from regular bedded sediments by: (i) irregular, disintegrated,  
401 or sheared contacts, (ii) incorporation of poorly sorted mud-rich matrix into clasts, and (iii) juxtaposition  
402 of clasts of different facies (e.g. Fig. 7f). Structures within the unit include soft-sediment deformation,  
403 microfaulting, injections, sheared clasts oriented mostly parallel to bedding, and sheared fabrics in the  
404 matrix (Fig. 5, 6, 7).

405

406 *Sub-facies D5 (discordant sandstones and brecciated mudstones)*

407 *Description:* Facies D5 is composed of a chaotic mixture of: (i) mudstones, (ii) sandstones, and (iii)  
408 mudstone-sandstone breccia. The mudstones form the main lithology, exhibiting bedded intervals, with  
409 planar and irregular contacts, folded and deformed intervals, and chaotic intervals disrupted by  
410 sandstones (Fig. 7j). The sandstones are very fine- to fine-grained, light grey, and discordant to the  
411 primary mudstone bedding (Fig. 6e, 7j). The contact between sandstone and mudstone is sharp and  
412 sometimes ptymatically folded, or irregular, with sheared mudstone clasts at contacts and sandstone  
413 grains incorporated into the surrounding mudstone (Fig. 7j, k). The mudstone-sandstone breccia  
414 consists of angular to sub-angular sandstone clasts within a mudstone matrix (Fig. 6e). Clasts range in  
415 size from 15 to <1 cm, with contacts between the mudstone and sandstone sharp (Fig. 6e).

416

417 *MSB bounding zones*

418 The basal surfaces of the MSB unit display either thin (<10 cm) zones of intense deformation or sharp  
419 contacts with the underlying substrate. Updip the basal contact is characterised by a sharp contact with  
420 small-scale injection dyke structures where a sand-rich debrite (D1) in MSB overlies a high-density  
421 turbidite in MSA (well M12; Fig. 7b). Downdip to the SE in well M16 the basal shear zone is  
422 characterised by an erosively-based, 10 cm-thick, highly sheared mud-rich debrite (D2) overlying a  
423 high-density turbidite in MSA (Fig. 4b, 7d). Sharp contacts between the underlying MSA sandstone  
424 turbidites and the MSB mud-rich debrites (D3) are observed farther downdip (well M1 and 12a-11, Fig.  
425 7h, o).

426 The top of the MSB unit is marked by an abrupt change from debrites or mudstones into banded, hybrid  
427 and remobilised beds of the MSC unit (see Fig. 4b, 6). In well M12, there is a sharp contact between  
428 MSB mudstones and thicker (~2 m) MSC remobilised beds (Fig. 6f). Above this, high-density turbidites  
429 dominate the upper reservoir zone. Well M16 displays a sharp contact between mudstones, and  
430 overlying banded beds that pass upwards into remobilised beds (Fig. 6g, h). Well M1 displays a sharp  
431 contact between mud-rich debrites (D4) and banded beds, which pass gradually upwards into high-  
432 density turbidites and hybrid-beds (Fig. 6i). The contact in well 12a-11 is not preserved in core, but the  
433 facies changes from mudstones to high-density turbidites. In the northern area of the field, well 211/7-  
434 1 comprises 8 m of interbedded Facies D5 and turbidite facies 1 and 2 (Fig. 6j, k, l).

435

#### 436 *MSB lateral variability*

437 The MSB-unit is lithologically variable across the Magnus field. In the central and southern areas of  
438 the field, the MSB unit is predominantly characterised by a sandy mudstone matrix (Facies D1-4). The  
439 isopach thickness map of MSB broadly follows the outline of MSA isopach (Fig. 7a, 15b). A change  
440 from sand- to mud rich debrite facies is observed between well 12a-9 and M12 (Fig. 9a). MSB is  
441 interpreted to pinch-out between M12 and 12-a14, located in the footwall of the Magnus Fault (Fig. 9a).  
442 In the northern area (e.g. well 7-1, Fig. 6e), the MSB is dominated by brecciated and injection fabrics  
443 (Facies D5), with an absence of Facies D1-4. In this area the MSB can also be correlated between wells  
444 7-1 and 7a-3 (~420 m), thinning towards 7a-6 (Fig. 9c).

445

#### 446 **MSB-unit Interpretation**

447 The facies characteristics, together with the deformation features at its base, suggest that the MSB is a  
448 debrite. The basal deformation in some parts of the central and southern areas support interpretation of  
449 a basal shear zone (see Butler et al. 2016; Hodgson et al., 2019). Elsewhere, the basal shear is expressed  
450 as a sharp surface. The absence of internal bounding surfaces or consistent changes in character suggest  
451 that the unit was transported and deposited *en masse* as a dominantly cohesive debris flow in a single

452 event, having sufficient yield strength to enable >1 m diameter ‘rafted’ block/clasts to be transported.  
453 The larger blocks were likely incorporated from either the source area or substrate entrainment during  
454 transport based on, (i) over-turned, folded or anomalous bedding or lamination dips, (ii) irregular  
455 contacts between blocks and debritic matrix, or (iii) incorporation of debritic matrix streaks or  
456 inclusions into the blocks. The change in facies downslope from sand-rich (Facies D1) (e.g. well M12,  
457 Fig. 6a), to mud-rich debrites with higher clay contents (e.g. well M1, Fig. 6d), may represent a  
458 longitudinal flow evolution to a more cohesive debris flow; as grains become increasingly  
459 disaggregated and mixed into the matrix, increasing the yield strength of the flow (Fig. 6). As the yield  
460 strength increased, larger clasts could be supported by the debris flow (e.g. Hampton 1975; Talling  
461 2013). This distribution supports a transport direction towards the SE (i.e. from well M12 to M1, Fig.  
462 7a). The trend from sand- to mud-rich debrite facies (D1-4) in the central and southern areas suggests a  
463 minimum runout distance of ~3.7 km between well 12a-9 and M12 (Fig. 9a).

464 The character of the MSB unit in the northern area is markedly different (Facies DB) when compared  
465 to the debritic textures (Facies D1-4) in the central (e.g. well M16) and southern (e.g. well 12a-11)  
466 areas. Observations of discordant sandstones, brecciation, and soft sediment folding in Facies D5  
467 suggest formation through hydraulic fracturing and injection processes (see Koša 2007; Satur & Hurst  
468 2007), and minor remobilisation through slumping (Fig. 6e, 7j), rather than a debris flow. This suggests  
469 Facies D5 was either: (i) detached from the main central and southern debris flow; (ii) represents a  
470 separate failure event or the injected margin of the MSB debrite; or (iii) that the MSB was either very  
471 thin or not preserved in the northern area and D5 represents the boundary between the MSA and MSC.

472 Clay content is a controlling factor in the strength of a debris flow, with highly cohesive flows resistive  
473 to mixing with the ambient seawater, and prone to hydroplaning (Mohrig et al. 1998; Talling 2013).  
474 The character of the basal shear zone in the central and southern areas of the Magnus Field, suggests  
475 more erosion updip with lower clay content in the overlying deposit (i.e. Facies D1-2, Fig. 6b,d). The  
476 sharper basal contact downdip (wells M1 and 12a-11 (Fig. 7h, o)) could suggest less erosion with higher  
477 clay contents in the overlying deposit (i.e. Facies D3-4, Fig. 7h). This may support a debris flow  
478 transported from the NW that was able to erode into a likely unlithified/semi-lithified substrate  
479 (primarily MSA reservoir unit), which evolved longitudinally into a highly cohesive debris flow that  
480 was prone to hydroplaning. Hydroplaning, enables debris flows to detach from the underlying substrate,  
481 and to bypass with limited or no transmission of shear stress beneath the flow (see “free-slip flows”  
482 Sobiesiak et al. 2018). Field studies of similar sized deposits (i.e. 10’s m thick) show debrites can have  
483 heterogeneous basal zones including sharp, discordant, and erosive contacts (e.g. Auchter et al. 2016).

484  
485

## 486 **PETROPHYSICS & PETROGRAPHIC ANALYSIS**

487

### 488 **Petrophysical properties of the MSM**

489 Here, we build on the core facies analysis outlined above by using well-log and biostratigraphic data to  
490 correlate the lower reservoir (MSA), intra-reservoir MTD (MSB), upper reservoir (MSC, E, G, & H),  
491 and mud-prone units (MSD & F) across the Magnus Field, thereby establishing their spatial distribution  
492 and thickness (Fig. 8, 9).

493

#### 494 *Lower reservoir (MSA)*

495 The lower reservoir (MSA) is characterised by predominantly low gamma-ray (GR) values (<75 gAPI),  
496 indicating low volumes of shale (<1% average, derived from GR logs), and a neutron-density cross-  
497 over consistent with high-density turbidite sandstones (Facies 1) observed in core (Fig. 8a). The  
498 compressional (p-wave) velocity (i.e. sonic log) is approximately constant (c. 80-100  $\mu\text{s}/\text{ft}$ ) across the  
499 interval, and the high resistivity (c. 25-270  $\Omega\text{m}$ ) and oil saturation (0.79, derived from resistivity in well  
500 M16) is consistent with oil staining observed in the core (see fluorescence emission in Facies 1, Fig. 5).  
501 Breaks in these responses are rare and interpreted to represent the transitions between turbidite  
502 packages, characterised by higher gamma-ray values and limited separation between neutron-density  
503 (see Fig. 8a). These breaks correlate with the mudclast-rich intervals identified from core in Facies 1  
504 (Fig. 5). The responses are consistent with an interpretation of predominantly amalgamated high-density  
505 turbidites in the central area of the field (Fig. 9a). Away from the central trend of the field (i.e. Fig. 9a),  
506 log values become more variable with increasing GR values (>75 gAPI), and neutron-density cross-  
507 overs (e.g. M1 and M2, Fig. 7a, 9e). Calibrating these responses with core shows that variable responses  
508 in MSA can be attributed to thin-bedded low-density turbidites (Facies 2) and background mudstones  
509 (Facies 6) (see Fig. 7r). Core plugs from high-density turbidites (Facies 1) display an average porosity  
510 = 22%, average vertical permeability ( $K_v$ ) = 500 mD, and average horizontal ( $K_h$ ) permeability = 600  
511 mD.

512

#### 513 *Intra-reservoir seal (MSB)*

514 The MSB is characterised by relatively high (>75-250 gAPI) gamma-ray values, related to high volumes  
515 of clays within the debrite matrix of Facies 7 (Table. 2). However, the petrophysical expression of MSB  
516 can vary depending on well location, with updip wells (e.g. M16 & M12, Fig. 9a) characterised by an  
517 upwards increase in GR (75->150 gAPI), and downdip wells by a more consistent GR response (e.g.  
518 >125 gAPI, M1 & M8z, Fig. 9a). We attribute the distal expression to reflect increased mixing of clays

519 with increasing transport distance (Fig. 6a-d). Neutron-density cross-overs reverse when compared to  
520 the MSA, suggesting a predominantly clay-rich unit. Compressional velocities show an irregular  
521 signature, and resistivity values (1-2  $\Omega\text{m}$ ) are less than in MSA, likely related to a combination of no  
522 hydrocarbon saturation, and increased saturation of conductive brine and clay minerals. However, there  
523 are resistivity peaks (c. 10  $\Omega\text{m}$ ) in the basal zone of MSB, which are similar to those seen in studies of  
524 more shallowly buried MTDs in other basins (e.g. Sawyer et al. 2009).

525

#### 526 *Upper reservoir (MSC, E, G, & H) and mud-prone (MSD & MSF) units*

527 The upper reservoir sand-rich units (MSC, E, G, & H) are similar to MSA, with generally low GR  
528 values (45-80 gAPI), and neutron-density crossings consistent with sandstones. However, this  
529 expression can be more variable, likely related to more variable facies (i.e. Facies 3, 4, and 5) when  
530 compared to the high-density turbidite-dominated lower reservoir (MSA). The upper reservoirs can be  
531 interpreted as three turbidite-dominated sequences, split by zones of increased clay content (MSD and  
532 MSF). MSD/F are characterised by elevated GR (c. 100 gAPI), and reduced resistivity responses (c. 4  
533  $\Omega\text{m}$ ). Core data show MSD and MSF are dominated by hybrid, banded, and remobilised beds, and low-  
534 density turbidites, which are likely more conductive than high-density turbidites; this explains the  
535 observed reduction in resistivity. MSF can be correlated across the basin, and its top coincides with the  
536 *Iathetica re-influx* (Partington et al. 1993), whereas MSD is discontinuous across the basin. Low-density  
537 turbidites contribute little to the primary reservoir and in cases are not oil-stained (core  $\Phi = 15\%$ ,  $K_v =$   
538  $\sim 400$  mD,  $K_h = \sim 575$  mD), suggesting they are isolated from the main reservoir. Core plug samples of  
539 the H1 intervals of hybrid-beds, show these deposits have good porosity (16-24%) and moderate  
540 permeability ( $K_h = 20$ -200 mD). Banded beds (Facies 4) near the basal section of the upper reservoir  
541 (Fig. 6g, i) show more varied, typically lower porosities (>1-24%) and permeabilities ( $K_v = \sim 0.27$  mD;  
542  $K_h = \sim 21$  mD).

543

#### 544 **Fluid pressures: temporal and spatial variability**

545 Formation pressure in the Magnus reservoir is known to be highly variable due to sealing faults and  
546 clay-rich laterally extensive deposits (Atkinson 1985; Shepherd et al. 1990; Morris et al. 1999). Initial  
547 reservoir pressure was 6635 psi, at 3050 m, with a gradient of 0.67 psi/ft (Shepherd 1991). Figure 10d  
548 details the production history of the field and the operational timescales of the wells discussed below.

549 In early production wells, repeat formation tester pressure data display marked pressure breaks between  
550 the upper and lower reservoirs (Fig. 10a). For example, in well 211/12a-M1, the upper reservoir pressure  
551 gradient (0.34 psi/ft) follows a linear trend until the top of MSB (Fig. 10a). The lower reservoir  
552 pressure measurement increase significantly above a linear trend from the upper reservoir gradient. This

553 major pressure break (430 psia) suggests that MSB is acting as a barrier, compartmentalising the upper  
554 and lower reservoirs (Fig. 10a). Similar trends are also observed in other early production wells, with  
555 ranges in pressure breaks varying from 1984 psia in well M4, to 377 psia in well M12 (Fig. 10a). Mid-  
556 production wells show much lower pressure breaks (e.g. 22 psia in well M16), in effect following the  
557 upper reservoir pressure gradient, and in many late infill wells a negative pressure differential (e.g.  
558 M31z -1976 psia) is observed between the upper and lower reservoirs (Fig. 10b).

559 This variability in pressure change ( $\Delta p$ ) can be related to oil field management and operational activities  
560 (i.e. production and water injection, EnQuest Internal Report), and sealing faults that may serve to  
561 laterally compartmentalise the reservoir. There was an initial increase in the  $\Delta p$  trend (wells M1 to M5)  
562 related to rapid depletion of the upper reservoir prior to the full field-wide impact of water injection  
563 (Fig. 10b), pressure differences within the reservoir is represented by variable  $\Delta p$  values between wells  
564 M5 to M12 (Fig. 10b). The later negative  $\Delta p$  (wells M30 to M41) can be related to significant water  
565 injection into the upper reservoir, and limited water injection into the depleting lower reservoir during  
566 mid to late production (EnQuest Internal Report). No correlation between  $\Delta p$  and MSB thickness was  
567 found, suggesting MSB variability (within the areas sampled) has little impact on the unit's ability to  
568 act as a competent barrier on production timescales (Fig. 10c). Therefore, we can confidently infer that  
569 the MSB unit is acting as a fluid flow barrier across >7.5 km of the field. However, fluid pressure data  
570 in wells to the north (i.e. 7-1 and 7a-3) do not sample below MSC, therefore we cannot confirm whether  
571 or not the MSB (i.e. Facies D5, Fig. 6e, 7k) is sealing in this area. Overall, the pressure differentials  
572 suggest the MSB is a competent barrier in the central and southern areas of the field.

573 Vertical changes in formation pressure are also observed around MSF, which acts as a local pressure  
574 barrier (Fig. 10a). For example, wells M4, M9 and M16 show negative pressure breaks (-201, -242, and  
575 -10 psia respectively) between MSG and MSE (Fig. 10a). MSD also records vertical changes in  
576 formation pressure. However, breaks are not observed consistently, which we interpret to be related to  
577 the heterogeneity of facies (i.e. Facies 2, 3, 4 and 5) within MSF and MSD. In addition, pressure breaks  
578 are not observed in initial production wells (e.g. M1, Fig. 10a) suggesting that they are related to  
579 differential pressure depletion between zones of the upper reservoir during production, rather than  
580 virgin pressures (e.g. M16, Fig. 10a). In addition to the defined reservoir zones of the Magnus Field  
581 (see Fig. 3e) formation pressure plots also show intra-zone pressure breaks, which correlate with smaller  
582 sub-zones dominated by mudstones or transitional flow deposits (Fig. 10a). These variable pressured  
583 sub-zones also validate observed preferential water breakthrough along highly permeable sandstones  
584 during early production wells (see well M4, Fig. 10, EnQuest Internal Report).

585

586 **Petrographic properties of the MSM**

587 Core porosity ( $\phi$ ) and permeability (vertical  $K_v$  or horizontal  $K_h$ ) cross-plots can help identify flow units  
588 within a reservoir (Fig. 8b). However, in reservoirs such as the MSM, with c. 60-85% sandstone, there  
589 is obviously a distortion in the dataset with respect to core plug samples (Fig. 9). Thus data are skewed  
590 towards sandstone-dominated units, transitional flow deposits (Facies 5, 4, & 5) are underrepresented,  
591 and debrite samples (Facies 7) are absent.

592 We therefore used QEMSCAN to quantify the difference in mineralogy, grain size, and porosity of  
593 facies sampled from well 211/12a-M16 (Fig. 2). In addition, QEMSCAN also allows analysis of  
594 depositional textures, particularly useful for debrites. Fourteen samples were collected (QM1 to QM14,  
595 see Fig. 4a for depths). Sample QM10 recorded scanning errors due to sample damage, thus its results  
596 are considered unreliable (see Fig. 14a). The grain-size distribution in QM6 is also artificially skewed  
597 towards the coarser end of the grainsize spectrum as some grain-grain contacts could not be resolved  
598 by the image-processing software (Fig. 13). The field of view in the mineral maps (QEMSCAN images)  
599 is approximately 2×2 cm (Fig. 11 & 12). The data is 2D and hence permeability cannot be quantified.  
600 An index of core images showing exact sample depths of QM1-14 can be found in the Supplementary  
601 Material.

602

603 *Mineralogy*

604 Using a quartz-feldspar-lithics ternary plot, MSM samples fall within the sub-arkose, arkose, lithic  
605 arkose, and feldspathic litharenite categories (Fig. 14b). Lithics were calculated by summing all other  
606 mineral percentages excluding clays, which are predominantly authigenic (e.g. kaolinite and illite) (see  
607 Fallick et al. 1993). Quartz is the dominant detrital mineral (c. 20-60%), apart from QM9, which  
608 sampled a mud-rich debrite with c. 30% illite. The high-density turbidite samples (QM6 & 14) and the  
609 hybrid-bed basal sandstone (QM12) (Facies 1, 2, & 5), plot within the arkose to sub-arkose category.  
610 All have low (<10%) amounts of lithics. Debrites (QM5, 7, 9), and the banded bed (QM8) samples, all  
611 display a high proportion of lithics spanning the lithic arkose to feldspathic arenite categories.  
612 Diagenetic clay overgrowths are present in all turbidite samples, but are generally minor (e.g. 1.85%  
613 illite, QM1), increasing in proportion when grain size decreases (e.g. c. 6% illite, QM4), with samples  
614 displaying pore-bridging illite fabrics (see QM2, Fig. 11). In the basal hybrid bed sandstone, clay  
615 content increases upward accompanying a transition from H1-to-H3 (QM12, Fig.12, Fig.5) (see  
616 Haughton et al. 2009). Heavy mineral content (zircon, iron oxides, and apatite) shows no distinct change  
617 or trend between the lower (QM1-4), MSB (QM5-9), and upper reservoir (QM11-14).

618

619 *Grain-size distributions & reservoir quality*

620 Grain size distributions were extracted from QEMSCAN images. Our samples span a range of  
621 grainsizes, from 1-20  $\mu\text{m}$  (clay-silt) to >1000  $\mu\text{m}$  (very coarse sand). Distributions can appear skewed  
622 towards coarser or finer populations or may approximate a normal (gaussian) distribution (Fig. 13). As  
623 expected, high-density turbidites (Facies 1) show a skew towards coarser (>125  $\mu\text{m}$ ) grain size  
624 populations (QM1-4, Fig. 13). There is, however, some variability depending on precisely where in the  
625 bed the sample comes from (e.g. QM11 vs. QM1, Fig. 13). QM11, which is taken from the base of a  
626 bed, displays a significant coarse-grained skew, with most of the grains >250  $\mu\text{m}$ , whereas samples  
627 from middle and upper parts of turbidite beds have normal distributions (e.g. QM13, Fig. 13). A low-  
628 density turbidite sampled by QM14 shows a fine-grained skew, with silt and very fine sand dominating  
629 the sample. The hybrid-bed (H1) shows a finer skew than high-density turbidites, with no sand grade  
630 over medium (QM12, Fig. 13). QM12 also shows a distinct normal grading, increasing in fines towards  
631 the top of the sample (Fig. 12). The banded bed sample shows a similar trend to QM14, with distinct  
632 grain size breaks visible in the mineral maps (QM8, Fig. 12). The MSB debritic matrix demonstrates a  
633 broadly normal distribution of grain sizes in samples QM5 and QM7, with the grain size ranging from  
634 coarse sand to clay-silt grade material. QM9 samples the mud-rich debrite part of MSB, showing an  
635 increase in clay-silt grade material, and imbricated/shear fabrics (Fig. 12).

636 Clay content is defined by a combination of the percentage of glauconite, illite, chlorite, kaolinite,  
637 smectite, and other secondary clays (see Supplementary Material). Total clay versus total porosity  
638 demonstrates a strong, positive relationship ( $R^2=0.84$ ). High porosity (17-26.5%) and low clay content  
639 (<10%) characterise the high-density turbidite samples, consistent with the primary reservoir facies  
640 (Fig. 14a). In the thin-bedded turbidite sample (QM14), detrital and diagenetic clays exceed 40%,  
641 reducing porosity to <5% and rendering them ineffective reservoirs. The hybrid-bed sample (QM12)  
642 clay content is elevated when compared to high-density turbidites, with a porosity of c. 15%; such  
643 deposits may therefore still contribute to net pay (Fig. 14a). Core porosity and permeability  
644 measurements from hybrid beds demonstrate they may act as reservoirs in the cases of the lower most  
645 sandstone divisions (H1) (c.  $\Phi = 20\%$ ,  $K_h = 200$  mD), with debritic divisions (H3) acting as baffles (c.  
646  $\Phi = 9\%$ ,  $K_h = 10$  mD). Debrites and banded beds show high clay fractions (>37%), and low total  
647 porosities (<10%), and likely insignificant effective porosity, with connectivity between pore throats  
648 limited (Fig. 13, 14a). It must be noted that the sample dataset is small and spatially restricted to well  
649 M16. Therefore, these data show the potential of using QEMSCAN methods to characterise reservoir  
650 quality, but more samples would be needed to draw field-wide trends.

651

652

## 653 **SEISMIC ANALYSIS OF THE MSM RESERVOIR**

654

655 Seismic facies analysis of the MSM reservoir supports a slope to basinfloor environment, which is  
656 consistent with previous studies of the Magnus Field (e.g. Shepherd et al. 1990; Ravnås & Steel 1997).  
657 This is illustrated in the context of two seismic units: (i) the lower reservoir (Top Heather to Base MSB  
658 interval), and (ii) the upper reservoir (Base MSB to the BCU interval) (Fig. 2).

659

### 660 **Lower reservoir**

661 The lower reservoir comprises the MSA plus Lower Kimmeridge Clay Formation (Figs. 2 and 3) and  
662 is defined by a centrally located depocentre (up to 285 m thick), which is partially confined by WNW-  
663 ESE striking faults, and the N-trending Brent Fault High (Fig. 15). The updip (i.e. to the NW) edge of  
664 this interval is characterised by a narrow isopach thick, whereas downdip it thickens into a broader  
665 depocentre (Fig. 15b). The downdip (i.e. to the SE) thickening of the MSA in the central area coincides  
666 with an increase in the proportion of high density turbidites (c. 20 m to >150 m, Fig. 9a), whereas  
667 thinner sequences characterise southern and northern areas (c. <25 m, Fig. 9b, c). The WNW-ESE  
668 striking faults do not offset the MSA reservoir, but instead tip-out in the Lower Kimmeridge Clay  
669 Formation, with stratal thickening into the faults. Hence, these faults were not active, but formed an  
670 irregular topography that shaped the distribution of the MSA (Fig. 15a). The seismic character of the  
671 MSA displays a clear updip to downdip transition. The updip area comprises a confined (650 m wide),  
672 continuous, high-amplitude and low acoustic impedance reflection (Fig. 15a, X-X'). This reflection  
673 exhibits a mounded geometry with positive relief, reflecting differential compaction around sandstone-  
674 rich fairways (i.e. wells M12 and M16, Fig 9a). Further downdip, the MSA reflection initially widens  
675 (c. 1.5 km) (Fig. 15a, Y-Y') and then transitions into two reflections with high-amplitude and high  
676 continuity in the central area and lower amplitude and thinning to the north and south (Fig. 15a, Z-Z').  
677 Amplitude extractions taken from the top MSA show the distribution of the reservoir, imaging a  
678 centrally confined channel form in an inferred upper to mid-slope position, expanding downdip into a  
679 lobate geometry (c. 10.25 km<sup>2</sup>) (Fig. 15b, -30 m offset). The system then backsteps up the slope, until  
680 there is no reservoir amplitude response, marking the boundary with the mud-prone MSB (Fig. 15b, -  
681 10 m offset). The gross geometry of the MSA is consistent with the petrophysical and core analysis,  
682 which shows a predominance of high density turbidites in the central MSA fairway area, and more mud-  
683 rich thin-bedded turbidites (Facies 2), injectites, and background mudstones (Facies 6) farther downdip  
684 and along strike (i.e. northern and southern areas).

685

686 **Upper reservoir**

687 The upper reservoir comprises the upper MSM (Base MSB to Upper Kimmeridge Clay Formation/BCU  
688 interval; Figs. 2 and 3), which is split into two depocentres, trending along the axis of the Penguin half-  
689 graben: (i) a southern depocentre within the hanging-wall of the Brent Fault, and (ii) a north-eastern  
690 depocentre (Fig. 16b). The Brent Fault tips out within the MSM, and was active during the deposition  
691 of the upper reservoir based on thickening into its hanging-wall (Fig. 16a, Y-Y<sup>1</sup>). The reflection are  
692 high-amplitude but contain both high and low acoustic impedance responses that are more  
693 discontinuous than the lower reservoir (Fig. 16a, X-X'). Amplitude extractions from near top MSM,  
694 show high amplitudes are truncated by the BCU (Fig. 16b, -20 m). Amplitudes trend SW, increasing  
695 from isolated linear forms to more connected responses, suggesting a possible change in the sediment  
696 supply direction when compared to MSA (Fig. 16b, -50 m). The upper reservoir is more heterogeneous  
697 than the lower reservoir, preventing calibration of individual facies to the seismic response. However,  
698 backstepping of the system to the NE is inferred from an absence of high amplitudes in the south near  
699 the top of the reservoir (Fig. 16b, -50 m to -20 m). The upper MSM is overlain by a continuous high-  
700 amplitude response in the south-east of the field (Fig. 16b), which is interpreted as the Upper  
701 Kimmeridge Clay Formation (Fig. 9f).

702 The upper reservoir also contains several footwall-collapse structures, which can be interpreted as an  
703 MTC (i.e. seismic-scale MTDs), with hummocky upper surfaces and high amplitude basal shear zones  
704 (Fig. 17) (e.g. Bull et al. 2009; Steventon et al. 2019). The intact rotated blocks and discrete faulting  
705 suggests the MTC was emplaced by slump processes (e.g. Mulder & Cochonat 1996). In some slumped  
706 areas, updip extensional faults, which offset the BCU and detach into the MSB mudstone-rich unit,  
707 create a complex reservoir architecture in areas affected by footwall degradation (Fig. 3d) (e.g.  
708 Underhill et al. 1997; McLeod & Underhill 1999).

709

710

711 **MSM Depositional Environment**

712 In this section we synthesise observations from core, petrophysical, petrographic, and seismic reflection  
713 data to interpret the overall stratigraphic evolution of the Magnus Sandstone Member in the Magnus  
714 Field, drawing on other field and subsurface studies where relevant.

715 In the lower reservoir, the combination of an updip channel form, and downdip lobate geometries, with  
716 the dominance of high-density turbidites (Facies 1) supports a depositional model with (1) sediment  
717 supply from the NW, (2) a central updip slope portion characterised by a confined submarine channel,  
718 and (3) a downdip toe-of-slope area represented by a turbidite lobe complex (Prélat et al. 2009) (Fig.  
719 15). The updip channel is dominated by coarse-grained lag deposits (well M12, Facies 1, Fig. 5),  
720 representative of proximal areas near sediment input points and channels where bypass of turbidity

721 currents is common (e.g. Stevenson et al. 2015). The downdip central area is also dominated by high  
722 density turbidite facies and is interpreted to represent the axis of a lobe complex. The mudclast-rich  
723 zones may represent boundaries between lobes (Fig. 5). Away from the central axial area, thin-bedded  
724 sandstones and background/turbidite mudstones are interpreted as off-axis to lobe fringe environments  
725 (Mutti 1977; Walker 1985; Kendrick 1998; Passey et al. 2006).

726 The MSB unit forms a barrier between the two reservoirs and is composed of predominantly mud-rich  
727 debrite, coeval with the *Autissiodorensis* maximum flooding surface (Fig. 7, 9). Unit MSB thickens SE,  
728 following the thickness trend of the lower reservoir, and becomes more mud-rich in this direction, we  
729 interpret the source area to be from the NW (Fig. 7a). This is consistent with the palaeo-dip of the slope  
730 to the SE (Fig. 3c, d). The Magnus dataset only covers part of the MSB, which extends across the  
731 Penguin half-graben (Morris et al. 1999). From the Magnus to Penguin-A Field, the MSB unit shows a  
732 thickening trend up to 33 m, terminating against the Penguin Horst (Al-Abry 2002). Al-Abry (2002)  
733 also notes the presence of debritic and slumped facies confined to the collapsed terrace areas of the  
734 Penguin Horst, relating their presence to slope instability, while noting other areas are dominated by  
735 background mudstones (Fig. 18b). This suggest that the debrite-rich MSB (i.e. Facies D1-4) in the  
736 Magnus area forms one of at least two debrites, initiated and transported towards the basin centre during  
737 a period of instability. We infer that the two debrite units are isolated to the slope and terrace areas of  
738 the Magnus and Penguin-A Fields respectively (Fig. 18b). Facies D5 in the northern area of the Magnus  
739 Field is interpreted to form as a separate deposit (Fig. 18b). Overall, we interpret the MSB to represent  
740 basin margin instability, likely triggered from normal faulting and oversteepening, after a period of sand  
741 starvation possibly related to relative sea-level rise (e.g. Piper et al. 1997; Strachan 2002; Grecula et al.  
742 2008).

743 The upper reservoir comprises at least two lobe complexes, separated by the mud-dominated MSD and  
744 MSF units (Figs. 9a and 16). The NE-trending linear amplitudes are interpreted as distributary channels,  
745 suggesting sediment supply from the NE (Fig 16b). However, an alternative interpretation may be that  
746 the linear amplitudes represent linked fault-bound depocentres that have focused sediment axially along  
747 the field. As the Brent Fault was an active palaeo-high during deposition, it is likely the southern  
748 depocentre input point was near the original lower reservoir channel, whereas the northern depocentre  
749 was located NE of the Magnus Field (Fig. 16b). Facies within the upper reservoir are dominated by  
750 high-density turbidites, with thin-bedded sandstones, banded, hybrid and remobilised deposits common  
751 in both the MSD and MSF units. In other studies, banded beds have been observed at the transition  
752 between lobe axis and off-axis settings (e.g. Spychala et al. 2017b), or in proximal lobe settings (e.g.  
753 Stevenson et al. 2020). In the upper reservoir banded sandstone beds are concentrated above the mud-  
754 rich MSB unit (see Fig. 6f-i) suggesting that banded sandstone beds in MSC represent initially turbulent  
755 sediment-gravity flows interacting with the mud-rich slope substrate of MSB (e.g. Davis et al. 2009;  
756 Stevenson et al. 2020). Hybrid and remobilised beds are typically diagnostic of frontal lobe fringe

757 environments (e.g. Barker et al. 2008; Spychala et al. 2017b), and may also mark fan initiation cycles  
758 (e.g. Hodgson 2009). In the Magnus Field, transitional flow deposits and low-density turbidites  
759 dominate in the lower MSC, MSD and MSF of central and southern wells (e.g. Fig. 6h, well M16), with  
760 fewer of these facies types in the northern area of the field (e.g. see Facies proportions, Fig. 9). This  
761 supports the overall upper reservoir system being sourced from the NE, with well 7-1 in a proximal and  
762 axial lobe location, supported by the dominance of high-density turbidites and limited number of  
763 transitional flow deposits (Fig. 6j-l, Fig. 9). This is supported by the distribution of high-amplitudes in  
764 the upper reservoir, which backstep to the NE (Fig. 16b). In the central and southern areas, we interpret  
765 the system to be in a predominantly axial lobe location, evidenced by the dominance of high-density  
766 turbidites. However, distinct mud-prone units (MSD and MSF) represent periods of lateral shift and/or  
767 system backstepping to the north, moving the central and southern areas into off-axis or distal positions,  
768 and therefore, promoting the deposition lobe fringe deposits. This interpretation is consistent with the  
769 Magnus Field being located on the basin margin of the Penguin half-graben. Similar observations were  
770 made farther north in the basin where high-density turbidite axial lobe deposition was correlated with  
771 lobe fringes dominated by transitional flow deposits (Haughton et al. 2003).

772

## 773 **DISCUSSION**

774

### 775 **Evolution of the submarine slope depositional system in the Magnus reservoir and wider Penguin** 776 **half-graben**

777 The MSM records a significant sediment pulse during relatively high subsidence rates in the Penguin  
778 half-graben (Al-Abry 2002), and is coeval with the uplift of the Nordfjord High (see Fig. 2 inset map)  
779 to the north west and Shetland Platform to the west (Ziegler 1990; Ravnås & Steel 1997). The MSM  
780 onlaps the Penguin Horst, indicating it was a paleo-high during deposition (Dominguez 2007).  
781 However, it is likely the Magnus and End of the World faults experienced only minor activity, or were  
782 in fact dormant during much of MSM deposition (Ravnås & Steel 1997) (Fig. 2, inset maps).  
783 Sedimentation during the MSM can be separated into four stages: (i) confined sediment input derived  
784 from the north-west, (ii) a period of relative sea-level rise and basin instability, (iii) a switching of  
785 sediment input to a northern province, and (iv) a further period of instability.

786 *Stage 1:* The lower reservoir (MSA) is characterised as a centrally restricted, fault-controlled channel-  
787 lobe complex, sourced from a single north-westerly input point (Fig. Fig. 15b & 9a). Probable hinterland  
788 source areas include the Magnus Basin (North Shetland Trough), which had not fully subsided at this  
789 time, and the Nordfjord High/Margareta Spur. Ravnås & Steel (1997) propose a fill-and-spill model for  
790 the MSM deposition, interpreting that the Magnus Basin had limited accommodation, promoting

791 sediment transport farther basinwards into the Penguin half-graben (Fig. 18a). An alternative  
792 interpretation is a sediment source from the Shetland Platform to the west, similar to other Upper  
793 Jurassic deep-water systems in the Moray Firth and Viking Graben (Shepherd et al. 1990).

794 *Stage 2:* MTDs are typically associated with shelf-edge and/or slope instability (e.g. Nemeč et al. 1988;  
795 Nemeč 1990; Mayall et al. 1992; Galloway 1998). The mud-rich character of the MSB debrite support  
796 its association with a period of reduced clastic input and precedes reorganisation of sediment supply  
797 from the north-west (lower reservoir) to the north (upper reservoir) (Fig. 18). Increased subsidence is  
798 likely during this time, due to fault population linkage correlating with the formation of the maximum  
799 flooding surface (*Autissiodorensis*), and an increase in hemipelagic radiolarian diversity (Morris et al.  
800 1999; Al-Abry 2002) (Fig. 9). Therefore, the preconditions to slope failure may have been relative sea-  
801 level rise and hemipelagic sedimentation, and slope steepening due to tectonism, with failure across a  
802 weak mud-rich layer (e.g. Bull et al. 2009; Spychala et al. 2017a). Similar debrite facies with starry-  
803 night textures have also been observed to compartmentalise other turbidite reservoirs in the North Sea  
804 (e.g. Britannia Field, Barker et al. 2008; Eggenhuisen et al. 2010), and in outcrop-based studies (e.g.  
805 Pickering & Corregidor 2005; Jackson & Johnson 2009; Auchter et al. 2016).

806 *Stage 3:* The input direction for the upper reservoir (MSC-H) is interpreted to change to the north-east,  
807 evidenced by the SW-trending seismic amplitudes and axial trending depocentres (Fig. 16b). This  
808 suggests a shift in sediment supply from north-west to north, with potential sources including the  
809 Makrell Horst/northern Penguin Ridge and the Magnet Ridge (Ravnås & Steel 1997; Gabrielsen et al.  
810 1999; Al-Abry 2002). However, heavy mineral percentages from QEMSCAN show no change between  
811 upper and lower reservoirs, which may suggest: (i) a change in sediment routeing pattern but not source  
812 area; (ii) a change in catchment area with eroded sediments being mineralogically consistent between  
813 the two areas; (iii) intrabasinal sediment storage and recycling; and/or (iv) updip mixing of multiple  
814 source terrains.

815 *Stage 4:* During the latest Jurassic to earliest Cretaceous, the basin transitioned from sand-rich MSM  
816 deposition into the mud-dominated Upper Kimmeridge Clay Formation. This transition is associated  
817 with the *Hudlestoni* maximum flooding surface (base J66), which can be correlated across the basin  
818 (Morris et al. 1999). This relative sea-level rise may be associated to the linkage of the Magnus and End  
819 of the World basin-bounding faults, related to the opening of the Magnus Basin (North Shetland  
820 Trough) and the Møre Basin, to the west of the study area (Fig. 17c). The observed slumping in the  
821 upper MSM was likely caused by increased activity on basin-bounding faults and associated uplift and  
822 tilting of their footwalls (Fig. 17).

823

## 824 **Identifying sealing sub-seismic MTDs**

825 Understanding of the sealing potential of MTDs is important for several applications including: (i) the  
826 distribution of reservoir-seal pairs, and stratigraphic traps during exploration, particularly on unstable  
827 basin slopes (e.g. Sabah, NW Borneo, Grecula et al. 2008), (ii) understanding reservoir  
828 compartmentalisation during hydrocarbon production, and (iii) subsurface pore pressure prediction and  
829 the correct placement of well engineering (e.g. casing shoes) during drilling operations. Numerous  
830 studies have shown the sealing capacity of seismic-scale MTDs (e.g. Flemings et al. 2008; Algar et al.  
831 2011; Dugan 2012; Day-Stirrat et al. 2013; Cardona et al. 2016; Sun et al. 2017; Wu et al. 2019). These  
832 studies highlight the importance of densification and shearing, causing enhanced alignment of clay  
833 minerals along basal shear zones, leading to a reduction in porosity and permeability. Through the  
834 analysis of core, petrophysical, and particularly pressure data, we have demonstrated the ability of a  
835 sub-seismic MTD (MSB) to act as a competent field-wide barrier to fluid flow.

836 Initial identification of abrupt pressure barriers between reservoirs or internally within a reservoir zone,  
837 is a useful method for identifying potential sealing-MTDs (Fig. 10a). Petrophysical logs should allow  
838 a distinction between mud-rich sub-seismic MTDs and slope mudstones. However, with increasing  
839 burial and compaction, along with hydrocarbon charge, log responses identified from studies of  
840 shallower sections (e.g. < 1 km) can become unreliable in predicting deeply buried sealing-MTD (e.g.  
841 Sawyer et al. 2009; Day-Stirrat et al. 2013). It should also be noted that wireline logging tools have a  
842 vertical resolution of ~0.15 m, and therefore, will only characterise trends throughout an MTD and not  
843 more subtle, core-scale heterogeneities (Table 2). Gamma-ray values are generally high (> 75 gAPI),  
844 related to high volumes of clay in the MTD matrix, but can be variable depending on the lithology of  
845 entrained clasts and large blocks. Density motifs in shallow studies are characterised by high values  
846 when compared to surrounding sediments, and peaks in the basal zone are attributed to shearing and  
847 over consolidation (Dugan 2012; Wu et al. 2019). In the Magnus Field, the MSB unit demonstrates  
848 higher densities than bounding sedimentary successions, similar to shallow studies (< 1 km). However,  
849 caution should be taken when using this approach below the sand/shale density crossover (~600 mbsf,  
850 Cook & Sawyer 2015), and in deeper formations, as sandstone can become much denser than shale,  
851 particularly during the onset of cementation (e.g. Avseth 2000). Neutron-density plots should display a  
852 cross-over with neutron to the left and density the right, indicating a shale response (Fig. 8a). In shallow  
853 studies, resistivity in MTDs is generally higher than background sediments and is particularly elevated  
854 in the basal zone (e.g. Day-Stirrat et al. 2013). This increase is attributed to densification and porosity  
855 loss when compared to background mudstones (Flemings et al. 2008; Dugan 2012). In this study, we  
856 observed a similar downward increase in resistivity within the MSB unit, with a peak in the basal zone  
857 (Fig. 8a). However, below the MSB resistivity increases further in the oil-filled MSA reservoir, and  
858 therefore, resistivity should not be a discriminating factor when identifying MTD-based hydrocarbon  
859 seals or barriers (Fig. 8a). MTD porosity should be low (<10%) (Fig. 4, PHIT), with possible isolated

860 high-porosity zones generated by entrained clasts (e.g. sample QM6, Fig. 14a). Volumes of clay are  
861 likely to be high (e.g. 37-57% in MSB, Fig. 14a).

862 Recognition of sub-seismic sealing MTDs should be undertaken through the integration of multiple  
863 datasets, particularly pressure measurements which provide a valuable dynamic validation of hydraulic  
864 sealing. For example in the Måløy Slope, offshore Norway, sub-seismic debrites and slumped units can  
865 be identified by integration of well-logs through electro-facies analysis (Prélat et al. 2015). The Buzzard  
866 Field, in the Central North Sea, shows how intra-reservoir mud-prone slump units were initially  
867 predicted to be sealing, however, during production bounding reservoir units were found to be in  
868 pressure communication (Ray et al. 2010). Hence, individual motifs from a single log or core sample  
869 alone cannot reliably indicate a sealing-MTD. Multiple log motifs and formation pressures should be  
870 observed in unison. In addition, MTDs are likely to show higher spatial and stratigraphic variability,  
871 when compared to background sediments.

872

### 873 **Lateral variability of the MSB and impact on later deposition**

#### 874 *Sources of mud for the MSB unit and younger transitional flows*

875 Mud-rich substrates and/or source areas are important for the development of laminar and transitional  
876 flows, in both the initiation stages of shear failure as in the case of MTDs, or during flow  
877 transformation(s) of hybrid, banded, and remobilised beds (e.g. Haughton et al. 2003; Davis et al. 2009).  
878 Flume tank experiments have shown the development of cohesive debris flows needs >10-15% of  
879 cohesive fines (<20-30  $\mu\text{m}$ ) (Talling 2013). The fines content of transitional flow deposits varies  
880 spatially, and can be explained through several mechanisms including: (i) deposition of coarser fractions  
881 during the initial flow, (ii) variation in substrate and entrainment of mud-rich fractions causing  
882 longitudinal flow transformation, (iii) failure of a heterogeneous source, and (iv) partial transformation  
883 of debris flows (Haughton et al. 2003; Barker et al. 2008). However, for both laminar and transitional  
884 flows, sources of cohesive muds are essential. The MSB and MSF units validate the importance of  
885 coring clay-rich units, and not initially assuming they represent background mudstone sedimentation.  
886 MSB also demonstrates that correlation of maximum flooding surfaces (e.g. *Autissiodorensis* of MSB)  
887 and hemipelagic radiolaria diversity do not necessarily equate to *in situ* hemipelagic mudstones. Morris  
888 et al. (1999) suggest the interpretation of microfossils within the MSB is not decisively hemipelagic,  
889 but rather a mix of hemipelagic and low-density mud-rich turbidites. This suggests that mudstones could  
890 have been sourced partially from hemipelagic sedimentation, and partially from mud-rich turbidites,  
891 during a period of relative sea-level rise (Fig. 15b, 18a). Volumes of mudstone deposited by muddy  
892 turbulent flows can be significant (10s m), even near sediment entry points (see Boulesteix et al. 2019).  
893 In the case of the MSB unit, it is probable that hemipelagic sediments and muddy turbidites were  
894 remobilised and entrained into the interpreted cohesive debris flow (MSB). This suggests the Penguin

895 half-graben experienced variability in the thickness and source of mudstone sedimentation, both during  
896 and after the deposition of the sand-grade MSA. Thus, the extent of the MSA may influence the lateral  
897 and downslope variability of the MSB, described below.

898

#### 899 *MTD lateral variability and sealing*

900 Sedimentation rates and a source of sediment for mass-transport is an important consideration, with  
901 many tectonically active margins experiencing low sedimentation rates recording limited mass-  
902 transport processes (e.g. Tappin et al. 2007). Laterally the MSB can be split into: (i) central and southern  
903 areas characterised by mud- and clast-rich debrites (Facies D1-4, Table 2), and (ii) a northern area  
904 characterised by injectites and slumping fabrics (Facies DB, Table 2, Fig. 17b). This observed  
905 variability correlates with the presence and composition of the underlying MSA reservoir (Fig. 7a). In  
906 the central and southern areas, deposition of sand- and mud-grade material from the MSA channel-lobe  
907 complex, would have enabled the debris flow to preferentially entrain sandy-substrate. This, combined  
908 with a subsequent relative sea-level rise (Partington et al. 1993) and fault activity (Al-Abry 2002),  
909 would provide preconditioning factors for shear failure and the development of a cohesive debris flow.  
910 Preferential entrainment of the axial part of channel-lobe systems during mass-transport has also been  
911 observed in other systems (e.g. Magdalena fan, offshore Columbia, Ortiz-Karpf et al. 2017).

912 The northern area experienced lower sedimentation rates during the MSA period, and was  
913 topographically elevated compared to the central and southern areas, hence the absence of cohesive  
914 debris flow deposits. As the northern MSA interval was not charged with oil, the MSB has not been  
915 dynamically tested as a barrier (e.g. well 7-1, 7a-3, Fig 7a). However, inclusion of sand injectite fabrics  
916 in the northern MSB may indicate the presence of larger injectites that can act as efficient fluid flow  
917 conduits between disconnected reservoir units, casting uncertainty on seal integrity in the area (e.g.  
918 Hurst & Cartwright 2007; Cobain et al. 2017; Dodd et al. 2019).

919 Understanding the lateral variability of clay-rich zones should be considered an important component  
920 of hydrocarbon seal evaluation. The MSB highlights the importance of this by demonstrating that in  
921 slope settings, laterally continuous clay-rich zones that are associated with maximum flooding surfaces  
922 do not always correlate with hemipelagic/pelagic sedimentation. The MSB demonstrates the potential  
923 for clay-rich sub-seismic MTDs to act as competent seals or barriers, but that lateral heterogeneities  
924 within such rock bodies can pose a risk to seal integrity. It should be noted that there is likely uncertainty  
925 in MSB short-scale variability (i.e. <10's m), which has been identified in field examples of other  
926 debrite rich intervals (e.g. Fonnesu et al. 2015; Aughter et al. 2016).

927

#### 928 *Flow-deposit interactions above the MSB*

929 Above the MSB unit, particularly in the central region of the Magnus Field, the stacking of transitional  
930 flow deposits and hybrid beds follows a common pattern (Fig. 6). The lower part of MSC is  
931 characterised by a transition between mud-rich debrites, and remobilised flows and/or banded beds,  
932 both of which are common in cores (e.g. Fig. 6, M1, M12, M16). This is consistent with flows entraining  
933 a mud-rich substrate after the emplacement of the MSB debrite, and the rerouting of the sediment  
934 transport system to a NE input leading to flow transformation. However, hybrid beds are most common  
935 after the initial transition, and are distributed throughout the upper reservoir interval. This is common  
936 when slopes are in constant out-of-equilibrium states, as was probably the case in the Penguin half-  
937 graben (Haughton et al. 2009).

938 Therefore, we suggest an idealised stacking pattern after the deposition of a mud-rich MTD, whereby  
939 flows are prone to transformation, leading to the preferential deposition of transitional flow deposits  
940 (Fig 19f). This idealised stacking pattern implies that the paleo-seabed was mud-rich and the  
941 emplacement of the MSB debrite likely modified pre-existing sediment dispersal patterns, forcing flows  
942 through poorly established routing systems. These two factors may explain how turbulent flows were  
943 preferentially susceptible to becoming charged with mud and transformed into transitional flow types  
944 in the lower part of the MSC. The preferential development of transitional flow deposits directly above  
945 mud-rich MTDs is important for the reservoir potential of the lower MSC, which has been negatively  
946 impacted (see Fig. 14a, 19f). The recognition of this idealised stacking pattern may also be important  
947 for predicting the reservoir potential of other deep-water turbidite reservoirs.

948

949

## 950 **Reservoir architecture and transitional flow deposit heterogeneity**

951

952 The core porosity and permeability data, and QEMSCAN results support identification of principal  
953 reservoir facies (Facies 1, 2, and 4 ), and barriers/baffles (Facies 3, 4, 5 & 6) within the Magnus Field.  
954 Figure 14a demonstrates the influence of sediment gravity flow type on reservoir quality and shows a  
955 similar overall trend to other studies comparing sediment gravity flow mechanism and reservoir quality  
956 (Porten et al. 2016; Southern et al. 2017). Below we consider the reservoir architecture within the  
957 Magnus Field, and bed-scale heterogeneities of barriers and baffles, including their potential effects on  
958 Kv/Kh, reservoir modelling, and production from sand-rich submarine fans.

959

### 960 *Reservoir architecture*

961 Figure 19 summarises the reservoir architectures observed within the Magnus Field. The central area  
962 captures the full extent of the reservoir with a thick lower lobe complex (MSA), widespread debrite

963 deposition (MSB) and a full upper reservoir sequence (MSC-H) (Fig. 19a). In the southern area the  
964 lower reservoir is thin or absent and the upper reservoir is divided by the Brent Fault High. In the  
965 northern area, the lower reservoir is also thin or absent, and the upper reservoir's stratigraphic  
966 architecture is complicated by gravitational faulting and a distinctive MSB that we interpret to be  
967 confined to a small area of the slope (Fig. 18, 19). The central area of the lower reservoir is estimated  
968 to be composed of ~80-90% high-density turbidites, and therefore is highly homogeneous with no  
969 significant baffles impacting production ( $K_v/K_h \approx 0.8$ ) (Fig. 19e). The pressure data also shows that the  
970 MSB within the central and southern areas acts as a competent fluid flow barrier, compartmentalising  
971 the upper and lower reservoir (Fig 19e). Sealing faults are known to have split the field into numerous  
972 sectors with deep-seated (i.e. rift-related) extensional and thin-skinned slump faults (Fig. 17) impacting  
973 reservoir production (Shepherd et al. 1990).

974 In addition to these major features which were identified early in field development and production  
975 (e.g. De'Ath et al. 1981; Shepherd 1991; Morris et al. 1999) we also identify the role transitional flow  
976 deposits play in controlling vertical permeability and differential pressure depletion within the upper  
977 reservoir (Fig. 10). Shepherd et al. (1990) showed the significance of mudstones within the upper  
978 reservoir, which were observed to act a laterally extensive baffles to fluid flow, compartmentalising the  
979 field into four sand-rich reservoir units. Here, we can demonstrate that transitional flow deposits are  
980 also acting as intermittent pressure discontinuities, namely in the MSD and MSF, but also within  
981 subzones of the Magnus Field (Fig. 10a). The Magnus Field demonstrates how transitional flow deposits  
982 can impact vertical permeability, showing that they can isolate reservoir sandstones and negatively  
983 impact the sweep efficiency (i.e. the volume of reservoir "swept" by injected fluids, Lake 1989) during  
984 waterflooding and enhanced oil recovery (Fig. 10a).

985

#### 986 *Bed-scale heterogeneities and outcrop analogues*

987 Capturing bed-scale heterogeneities and the geometry of baffles and barriers is important for  
988 understanding reservoir properties, distribution, and sweep efficiency. Begg & King (1985) demonstrate  
989 the importance of characterising baffle dimensions, showing exponential relationships between  
990 increasing baffle dimension (i.e. thickness, width, length) and decreasing effective  $K_v$  (Fig. 19d). The  
991 3D nature of baffles and barriers is particularly important, as 2D reservoir simulations of impermeable  
992 heterogeneities often significantly overestimate their effect on reservoir production (see Jackson &  
993 Muggeridge 2000). A limitation of reservoir modelling is that many impermeable heterogeneities  
994 captured in core may be lost through the upscaling process during reservoir simulation, whereby a  
995 reservoir model (~50-100 m grid scale) aims to realistically capture 3D bed-scale heterogeneities (Fig  
996 19d). However, high resolution reservoir modelling and new technologies such as surface-based grids  
997 (e.g. Jackson et al. 2014; Jacquemyn et al. 2019) and adaptive reservoir model grids (e.g. Melnikova et

998 al. 2016) are beginning to allow reservoir models to realistically capture heterogeneities identified  
999 during wireline and core logging. To achieve this, outcrop analogues can be used to help improve our  
1000 understanding of baffle dimensions.

1001 In the Magnus reservoir we have identified several facies that act as baffles to fluid flow (Facies 2, 3,  
1002 4, 5) or, if amalgamated, as barriers (i.e. MSF) (Fig. 19e, Table. 2). However, we are not able to correlate  
1003 individual beds across the field. Outcrop examples of transitional flow deposits allow us to take  
1004 subsurface observations and compare these with possible analogues, where correlation along well  
1005 exposed outcrop allows confirmation of dimensions. The Ross Sandstone Formation, in county Clare,  
1006 Ireland, may provide a suitable outcrop analogue. The formation is composed of a sand-rich deep-water  
1007 channel-lobe system, with a relatively high-proportion of hybrid-event beds and MTDs (e.g. Pierce et  
1008 al. 2018). Studies focusing on lobe fringe environments in the Ross Sandstone Formation, where low-  
1009 density turbidites and hybrid beds dominate, show hybrid-event beds and MTDs can be correlated for  
1010 ~1 km (Pierce et al. 2018). Pyles & Jennette (2009) identify these fringe areas to have lower net to gross  
1011 and a higher proportion of MTDs. Other outcrop studies of transitional flow deposits include: the  
1012 Gottero Turbidite Sandstone in north-west Italy. Here, hybrid beds can be correlated for ~4 km, with  
1013 both laterally continuous and discontinuous morphologies (see Fonnesu et al. 2018). In the  
1014 Skoorsteenberg Formation, Karoo Basin, South Africa, hybrid beds are preferentially concentrated in  
1015 lobe fringe environments, where individual beds can be tracked for ~0.5-1 km, becoming amalgamated  
1016 updip and along-strike (Hodgson 2009; Spsychala et al., 2017).

1017 These outcrop examples demonstrate how transitional flow deposits may form 100's m scale baffles to  
1018 fluid flow. Studies of other Upper Jurassic North Sea turbidites reservoirs (e.g. Brae-Miller-Kingfisher  
1019 fan) have interpreted the debritic intervals of transitional flows to be widespread across the system,  
1020 evidenced by large exotic (i.e. non slope derived) clasts (Haughton et al. 2009). Therefore, assuming  
1021 the model of increasing thickness of H3 (i.e. debritic divisions) towards the lobe fringe (see Haughton  
1022 et al. 2003), it is likely that hybrid beds in the upper reservoir of the Magnus Field are laterally  
1023 continuous from mid-lobe to lobe fringe environments. This model is consistent with our observations  
1024 of pressures, where transitional flow deposits reduce the vertical permeability, connectivity of turbidite  
1025 facies, and sweep efficiency during production (Fig. 10, 19e). Amy et al. (2009) undertook a 2D  
1026 reservoir flow simulation of the Marnoso Arenacea Formation in northern Italy, composed of sheet-like  
1027 basinfloor turbidite sandstone with related transitional flow deposits. They similarly found beds  
1028 containing significant debritic material (porosity <15%, permeability <100 mD) which reduced  
1029 production efficiency and led to quicker water breakthrough. Our results highlight the importance of  
1030 characterising not just background mudstone but also other non-reservoir rocks. This is particularly true  
1031 for transitional flow deposits which are in most cases genetically related to the distribution of turbidite  
1032 reservoirs (e.g. Davis et al. 2009; Hodgson 2009; Spsychala et al. 2017b). These deposits should be

1033 properly characterised during reservoir modelling studies of turbidite channel-lobe systems, in order to  
1034 adequately capture the heterogeneities in rock properties and simulate fluid flow within a reservoir.

1035

1036

## 1037 **CONCLUSIONS**

1038

1039 (i) The evolution of the Magnus Sandstone Member's depositional system in the Penguin half-  
1040 graben can be divided into 4 main phases: *Phase 1* deposition of a centrally fault controlled  
1041 channel-lobe complex dominated by high-density turbidite facies, with a likely provenance  
1042 from the north-west, *Phase 2* a period of flooding, slope instability, and deposition of a mud-  
1043 rich debrite by a cohesive debris flow, *Phase 3* a shift of sediment supply from the north-west  
1044 to the north/north-east, and deposition of lobe complexes along the axial trend of the half-  
1045 graben, and *Phase 4* a relative sea level rise, basin tilting, and slumping within the Magnus  
1046 footwall. Post-rift thermal subsidence continued during the Cretaceous and Tertiary sequences.

1047

1048 (ii) Sub-seismic MTDs can act as competent fluid flow barriers at depth. Identification of such  
1049 deposits is best undertaken through the integration of fluid pressure, petrophysical, and core  
1050 data. Distinguishing features include abrupt pressure barriers between permeable flow units,  
1051 diagnostic motifs of logs (bulk density and resistivity) through comparison of MTDs with  
1052 background mudstones, variability in response across the deposit, high (>35%) volumes of clay,  
1053 and sedimentary structures associated with shear failure and mass-transport processes (e.g.  
1054 debritic textures, soft-sediment deformation, and sheared fabrics).

1055

1056 (iii) Evaluation of lateral variability within an MTD is critical in establishing its ability to act as a  
1057 competent barrier unit. The MSB unit demonstrates a stark contrast between mud-rich debritic  
1058 textures in the central and southern areas which are known to be sealing, and the northern area  
1059 where injection fabrics may provide fluid conduits between disconnected reservoir units. This  
1060 variability is also significant for reservoir development strategies and the prediction of fluid  
1061 pressure cells between reservoir segments.

1062

1063 (iv) Transitional flows may preferentially form above mud-rich substrates such as the MSB, where  
1064 turbulent flows are susceptible to becoming charged with cohesive mud. This produces an  
1065 idealised stacking pattern with transitional flow deposits (e.g. banded and remobilised beds)  
1066 occurring directly above mud-prone MTDs or other mud-rich substrates.

1067

1068 (v) Transitional flow deposits have been shown to act as intermittent barriers or baffles to fluid  
1069 flow. In the upper reservoir the deposits have compartmentalised the turbidite sandstone into  
1070 sub-zones, significantly reducing sweep efficiency and enhancing early water breakthrough.  
1071 Capturing these bed-scale heterogeneities during reservoir modelling is crucial for realistic  
1072 reservoir flow simulation and an effective field development strategy.

1073

## 1074 ***Acknowledgements***

1075 We would like to thank Equinor, EnQuest, and Rocktype for their funding, access to data and general  
1076 support throughout the project. The corresponding author would also like to thank the Geological  
1077 Society of London for research funding through the Daniel Pidgeon Fund. We would also like to thank  
1078 the Editors Caroline Hern and Kim Klitgord, and reviewers Neal Auchter, Martin Grecula, Mark  
1079 Bentley, and one anonymous reviewer for their constructive feedback which greatly improved the final  
1080 manuscript.

1081

## 1082 ***Data Access Statement***

1083 Some of the datasets generated during the current study are available through the OSF open-access  
1084 repository, <https://osf.io/2kfre/>. However, some of datasets analysed the current study are not publicly  
1085 available due to commercial confidentiality.

1086

1087

1088

## 1089 ***Figure captions***

1090 *Fig.1 – Conceptual models of MTDs effect on reservoir and seal distribution, (a) dip section of shelf-slope-basinfloor transect*  
1091 *with potential trapping mechanisms for turbidite slope channels, sheets, aprons, and basinfloor lobes from the Eocene shelf-*  
1092 *edge-slope-basinfloor transect, offshore Brazil (modified from Steventon et al. 2020), (b) strike section of MTD affecting lobe*  
1093 *reservoir distribution, observed from Temburong Formation, NW Borneo and Tres Paso Formation, Southern Chile (modified*  
1094 *from Jackson & Johnson 2009, Armitage & Jackson 2010) (c) idealised formation pressure and petrophysical responses of a*  
1095 *sealing-MTD.*

1096 *Fig.2 – (Left) Reservoir distribution map of the Magnus Field, note inset maps with field location in relation to the wider*  
1097 *structural framework, (Right) northern North Sea stratigraphic column of the Jurassic-Cretaceous, with studied section*  
1098 *highlighted in red. Volgian is a regional term approximately equivalent to the Tithonian. Collated from Shepherd et al. (1991),*  
1099 *Partington et al. (1993), Morris et al. (1999), Al-Abry (2002), and Dominguez et al. (2007).*

1100 *Fig.3: Field overview, (a) seismic dip section through the field (note: location X-X' found in Fig.2a), (b) geoseismic section*  
1101 *of principle seismic-stratigraphic units, note updip pinch-out and truncation of the MSM into the BCU, highlighting the*  
1102 *combination structural-stratigraphic trap, (c) Top Heather depth structure map with major normal fault arrays, (d) BCU depth*  
1103 *structure with late-syn rift normal faults and MTD headwall scarps and slump faults (see Fig. 17a), (e) summary of reservoir*  
1104 *units MSA to MSH from well 211/12a-M16.*

1105 *Fig.4: (a) Summary core logging sheet from 211/12a-M16 with main lithologies, reservoir units, and petrophysical responses.*  
1106 *Note positions of samples (QM) taken for QEMSCAN analysis. RHOB = bulk density, NPHI = neutron porosity, PHIT = total*  
1107 *porosity. (b) Detailed log of the MSB unit from well 211/12a-M16, note depths of core photos in Figure 6 & 7.*

1108 *Fig.5: Summary of turbidite (F1-2), transitional (F3-4), and debrite (D2-4) core facies observations.*

1109 *Fig.6: (a-d) core photos of the downslope longitudinal flow transformation of Facies D1-4 from sand-rich to clay-rich, (e)*  
1110 *core photo of facies D5 (see Table 2), (f-l) observations of the transition between MSB and MSC. Note green arrows marking*  
1111 *the contact, well 7-1 contact was not recovered during coring.*

1112 *Fig.7: (a) MSB thickness calculated from formation tops from wells, note the correlation between thickness and the outline of*  
1113 *the underlying MSA unit. (c-p) core photos capturing the heterogeneity within the MSB units. Note the basal shear zone (BSZ)*  
1114 *or contact between the MSA and MSB is marked by a green arrow, (r-q) example of axial and off-axis MSA.*

1115 *Fig.8: (a) Petrophysical log suite from 211/12a-M16 summarising the Magnus Reservoir, from left to right, GR = gamma-*  
1116 *ray, CALI = calliper, NPHI = neutron porosity, RHOB = bulk density, DRHO = density correction, DTCO = compressional*  
1117 *(sonic) velocity, RMEDI = medium resistivity, RDEEP = deep resistivity. (b) horizontal core permeability vs. core porosity,*  
1118 *and (c) vertical core permeability vs. core porosity.*

1119 *Fig.9: Reservoir correlation panels, (a-c) downdip correlations, (d-f) along-strike correlations. Note facies proportions in*  
1120 *logged wells, and biostratigraphic markers Autissiodorensis, Iathetica re-influx, and Hudlestoni.*

1121 *Fig.10: (a) formation fluid pressure plots, note pressure break associated with MSB, MSD, MSF and isolated transitional flow*  
1122 *deposits, (b) change in pressure observed between MSA and MSC, (c) plot of change in pressure between MSA and MSC vs.*  
1123 *MSB thickness, (D) production profile of the Magnus Field, including both oil production and water production (cut), note*  
1124 *activity timelines of wells.*

1125 *Fig. 11. Mineral maps and related porosity extractions of turbidite facies (HDT = high-density turbidites, VCL = volume of*  
1126 *clay). Field of view = 2×2 cm.*

1127 *Fig. 12. Mineral maps and related porosity extractions of laminar and transitional flow deposits (VCL = volume of clay).*  
1128 *Field of view = 2×2 cm.*

1129 *Fig.13: Grain-size distribution of quartz phases extracted from the QEMSCAN samples QM1-14 (see Fig. 4a for sample depths*  
1130 *within well M16).*

1131 *Fig.14: (a) QEMSCAN total volume of clay vs. porosity, note linear relationship, with turbulent facies having low clay and*  
1132 *high porosity values and debrites having high clay and low porosity values, (b) quartz-feldspar-lithics ternary plot of*  
1133 *QEMSCAN samples generally clustering around sub-arkose, arkose, lithic arkose, and feldspathic litharenite categories.*

1134 *Fig.15: (a) strike-orientated seismic sections imaging the evolution of the lower reservoir (MSA) from a confined updip*  
1135 *channel to distributive lobe complexes downdip, note sections are displayed using a coloured inversion cube, with high (hard)*  
1136 *acoustic impedances = blue, and low (soft) acoustic impedance = yellow, (b) thickness map highlighting the central isopach*  
1137 *thick of the lower reservoir, with sum of negative amplitude extractions highlighting the geometry and evolution of the MSA*  
1138 *reservoir channel-lobe system.*

1139 *Fig.16: (a) dip-orientated seismic sections highlighting the evolution of the upper reservoir (MSC-H), with the central section*  
1140 *(X-X1) imaging the depocentre to the north of the Brent Fault High, and the southern section (Y-Y1) imaging the syn-*  
1141 *depositional depocentre south of the high, note sections are displayed using a coloured inversion cube, with high (hard)*  
1142 *acoustic impedances = blue, and low (soft) acoustic impedance = yellow, (b) thickness map highlighting the southern and*  
1143 *northern isopach thicks, with RMS amplitude extractions highlighting the geometry and evolution of the upper reservoir and*  
1144 *the Upper Kimmeridge Clay Formation (UKCF).*

1145 *Fig.17: (a) northern dip-orientated seismic section of slumping within the upper reservoir, with extensional slump faults*  
1146 *detaching into the MSB, (b) southern dip-orientated seismic section with minor incision and slumping. Note slump faults*  
1147 *displace the BCU.*

1148 *Fig. 18: Basin evolution of the Penguin half-graben, (a) Lower reservoir point sourced from the north-west, (b) Intra-reservoir*  
1149 *MTD composed of debris flow from both the Magnus and Penguin Horsts, (c) Upper reservoir inferred to be sourced from the*  
1150 *north-east, with a local input point transporting sediment into the hanging-wall of the Brent Fault.*

1151 *Fig. 19: Synthesis of lateral variability in reservoir architecture (a-c) idealised cross-sections of the northern, central, and*  
1152 *southern reservoir architectures, (d/e) highlighting the difficulty of capturing core-scale heterogeneity in geological and*  
1153 *simulation grid scale reservoir models, with a grid cell only able to represent a single value for porosity and permeability,*  
1154 *with effective vertical permeability vs. baffle dimension showing the importance of understanding baffle dimension (modified*  
1155 *from Begg & King 1985), (f) summary of reservoir heterogeneity within the Magnus Field.*

1156

1157

1158

Table 1: Summary of reservoir sedimentology in the Magnus Sandstone Member (MSM). Note Kv/Kh ratios are calculated from core plug data.

Facies	Lithology	Thickness (m)	Sedimentology	Interpretation	Reservoir Unit (approx. $\Phi$ , Kv, Kh, VSH, Facies proportions %)
Thick-bedded sandstones (F1)	Fine-coarse grained sandstone, infrequent fine sandstone/siltstone caps	0.2->1.0 (amalgamated)	Massive or planar laminated sandstone, subtle normal grading, dewatering pipes/dishes, flame and load structures, with common bed amalgamation. Floating mudclast-rich horizons with sheared fabrics distributed throughout. Rarely preserved fine sand-silt grade ripple laminated bed tops.	<i>Process:</i> High-density turbidity currents (see Lowe 1982; Shanmugam 1996), <i>Environment:</i> forming in an axial submarine lobe position	<i>Primary reservoir</i> MSA & MSC-G Core $\Phi$ = 22% Log $\Phi$ = 29% Kv = 500 mD Kh = 600 mD Kv/Kh = 0.83 Log VSH = <1%
Basal sandstones (F1)	Medium sand to granule grade sandstones	<0.05-0.25	Sandstones, with weak to irregular grading, imbrication of granule/pebble material, and incisional/erosive bed bases	<i>Process:</i> tractional carpets at base of turbidity flow, <i>Environment:</i> basal lag deposit of submarine channel or bypass surface from the passage of turbidity currents (Walker 1984)	MSA & MSC-G Log $\Phi$ = 26% VSH = 3%
Thin-bedded sandstones (F2)	VF-Fine grained sandstone and siltstone, with mudstone caps	<0.05-0.2	Current ripple laminated sandstones, occasional flame and load or shear fabric structures at the base (Tc). Sharp normal grading from sandstone to silt and mudstones (T <sub>D/E</sub> ).	<i>Process:</i> Low-density turbidity currents (Mutti 1977), <i>Environment:</i> forming in an off-axis, submarine lobe and/or channel position (Jobe et al. 2012).	MSC-G Core $\Phi$ = 22% Log $\Phi$ = 15% Kv = 400 mD Kh = 575 mD Log VSH = 7-14%
Banded beds (F3)	Couplets of VF-Fine grained sandstone and siltstone, with mud-rich sandstones	<0.05-0.35	Distinctive alternating light/dark banding couplets. Light bands are often planar or ripple-cross laminated, sand-silt, upper contacts are either sharp or gradational, foundering structures common at base. Dark bands have elevated amounts of mudstone.	<i>Process:</i> Transitional flows, alternating between turbulent and laminar flows (Lowe & Guy 2000), <i>Environment:</i> submarine lobe sourced from and/or depositing on mud-rich substrate (Stevenson et al. 2020).	MSC-G Core $\Phi$ = 20 Log $\Phi$ = <1-24% Kv = 0.27 mD Kh = 21 mD Log VSH = 0-24%
Hybrid beds (F4)	Fine-medium sandstones and mud-rich sandstones	0.15-0.4	Lower sandstone beds graded or ungraded with loading structures at base (H1), dewatering pipes, and isolated mudclasts/chips at bed top.	<i>Process:</i> Hybrid event beds/linked debrites, transformation from turbulent	MSC-G (H1 & H3) Core $\Phi$ = 20 & 9% Log $\Phi$ = 0.23%

			Weakly laminated sandstone or banded bed divisions (H2). Sharp or sharp faulted contact into mud-rich sandstone with debritic texture, sand injections, oversized clasts, with sheared mud-stone clasts at the top of the bed (H3). Sharp irregular contact into parallel/ripple cross laminated fine sandstone and silt (H4). Sharp irregular contact into massive mudstone (H5).	to laminar flows (Haughton et al. 2003; Talling et al. 2004; Haughton et al. 2009), <i>Environment</i> : predominantly in distal/fringe submarine lobe positions (Hodgson 2009)	Kv = n/a Kh = 200, 10 mD Log VSH = <1%
Deformed-remobilised “slurry” beds (F5)	Fine grained sandstone, siltstones, and mud-rich sandstone	0.25-0.7	Sheared and folded internal fabrics, ball and pillow structures, relic banded bed (F5) sequences, highly shear mud clasts. Commonly occur in the same sequence as Banded beds (F5).	<i>Process</i> : Transitional flows, (Lowe & Guy (2000), with potential for post-depositional remobilisation (Barker et al. 2008), <i>Environment</i> : submarine lobe sourced from and/or depositing on mud-rich substrate	
Mudstones (F6)	Mudstone to siltstone	0.02->1.0	Homogeneous mudstones and/or finely (mm-scale) parallel laminated mudstones and siltstones. Contacts are usually sharp.	<i>Process</i> : hemipelagic settling and/or mud-rich turbidity currents (Stow & Shanmugam 1980; Boulesteix et al. 2019), <i>Environment</i> : slope and basin floor	MSA-MSG Log $\Phi$ = 0% VSH =90+%
Heterogeneous argillaceous beds (MSB) (see Table 6-2) (F7)	Chaotic Mud-rich sandstones, siltstones, and mudstones	1-18 (assuming a single event)	Poorly sorted mud-silt-sand matrix, with varying degrees of clay content from very dark grey/black (>50%), to light (<25%), matrix contains floating fine-medium sand-grade quartz, along with some granule to pebble grade clasts, producing a “starry night texture”. Structures include, sheared fabrics and mudstone clasts, injectites, soft-sediment deformation, micro-faulting, and irregular contacts with undeformed blocks of intact stratigraphy.	<i>Process</i> : mass-transport processes initiated from slope instability, predominately “well mixed” cohesive debris flows (Barker et al. 2008; Eggenhuisen et al. 2010), <i>Environment</i> : unstable submarine slope	MSB & F QEMSCAN $\Phi$ = 7% Log $\Phi$ = 6% Kv = n/a Kh = n/a Log VSH = 60%

Table 2: Summary of debrite (Facies 7) sedimentology

Sub-facies	Sedimentological character	Process Interpretation
Sand-rich debrite (D1)	Matrix supported mud-rich sandstones, with coarse sand to granule grade predominantly quartz making up the grains, with minor amounts of mudstone (clasts and sheared fabrics). Bed bases are occasionally grain supported. Sandstone and mudstone clasts are angular and often sheared.	<i>Process:</i> poorly cohesive debris flow, with sufficient yield strength to support ~0.5 m clasts, <i>Environment:</i> upper to mid slope.
Mud-rich debrites (D2-4)	Matrix supported mud-rich sandstones, with floating quartz clasts, and varying degrees of clay content. Intercalation of clasts and bedded sequences are common with varying degrees of disaggregation from minor soft sediment deformation to clast rich debrites. Often recognisable by “starry night” texture.	<i>Process:</i> cohesive debris flow (see Talling et al. 2014, M-2, ~100+ Pa yield strength), with enough strength to support 1+ m clasts, <i>Environment:</i> slope and base-of-slope in main MSA lobe complex depositional fairway
Facies (D5) injectite/breccia	Chaotic mix of mudstone-sandstone breccias, sandstones, and mudstones. Structures include soft sediment deformation and injection fabrics.	<i>Process:</i> hydraulic fracturing, injection, and minor slumping (e.g. Satur & Hurst 2007), <i>Environment:</i> off-axis of initial MSA depositional fairway.

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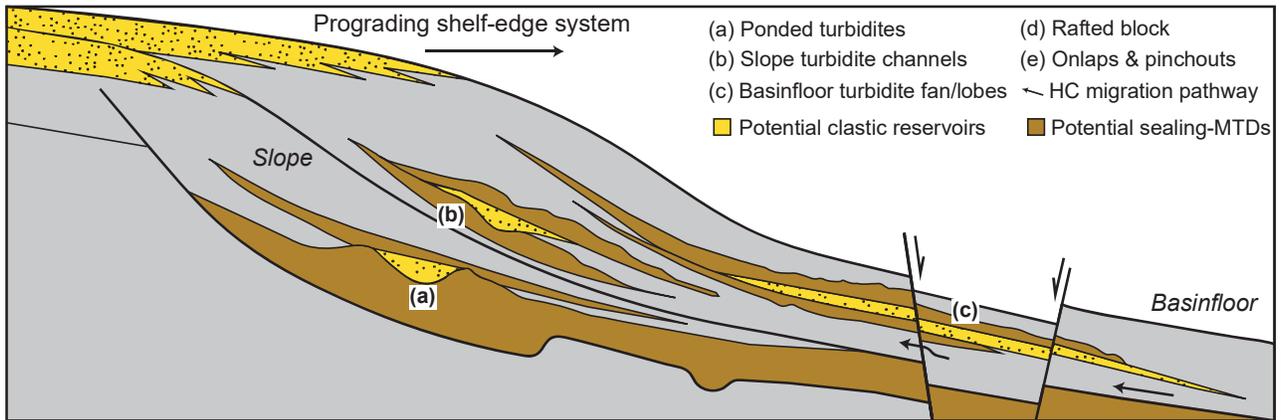
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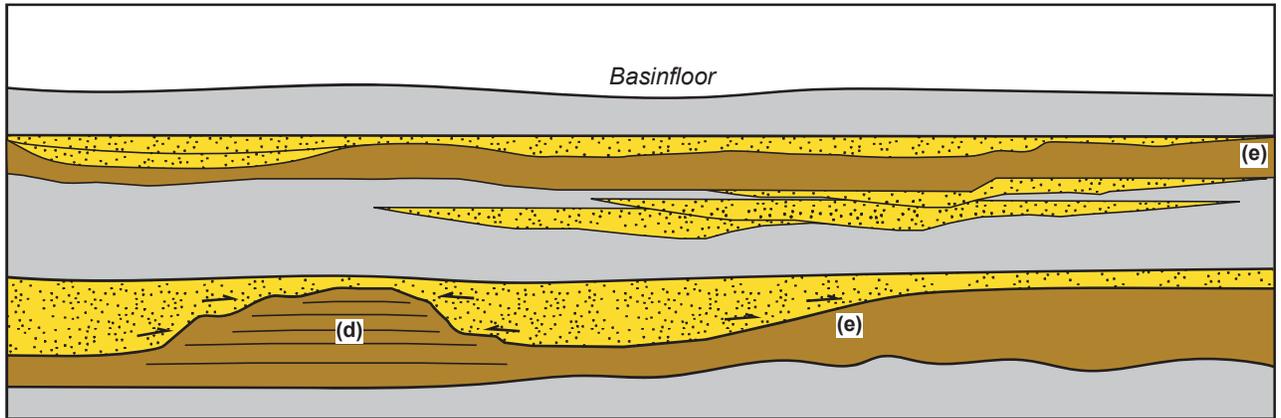
figure 1

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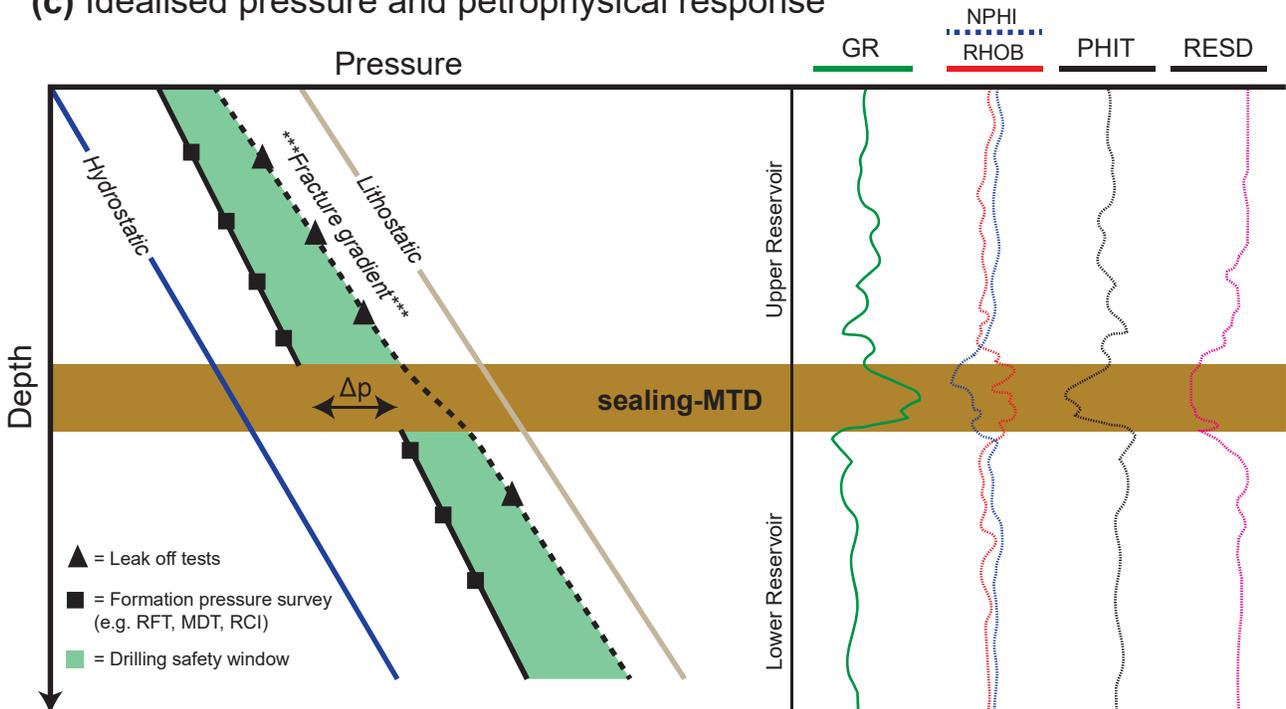
**(a) Dip section**

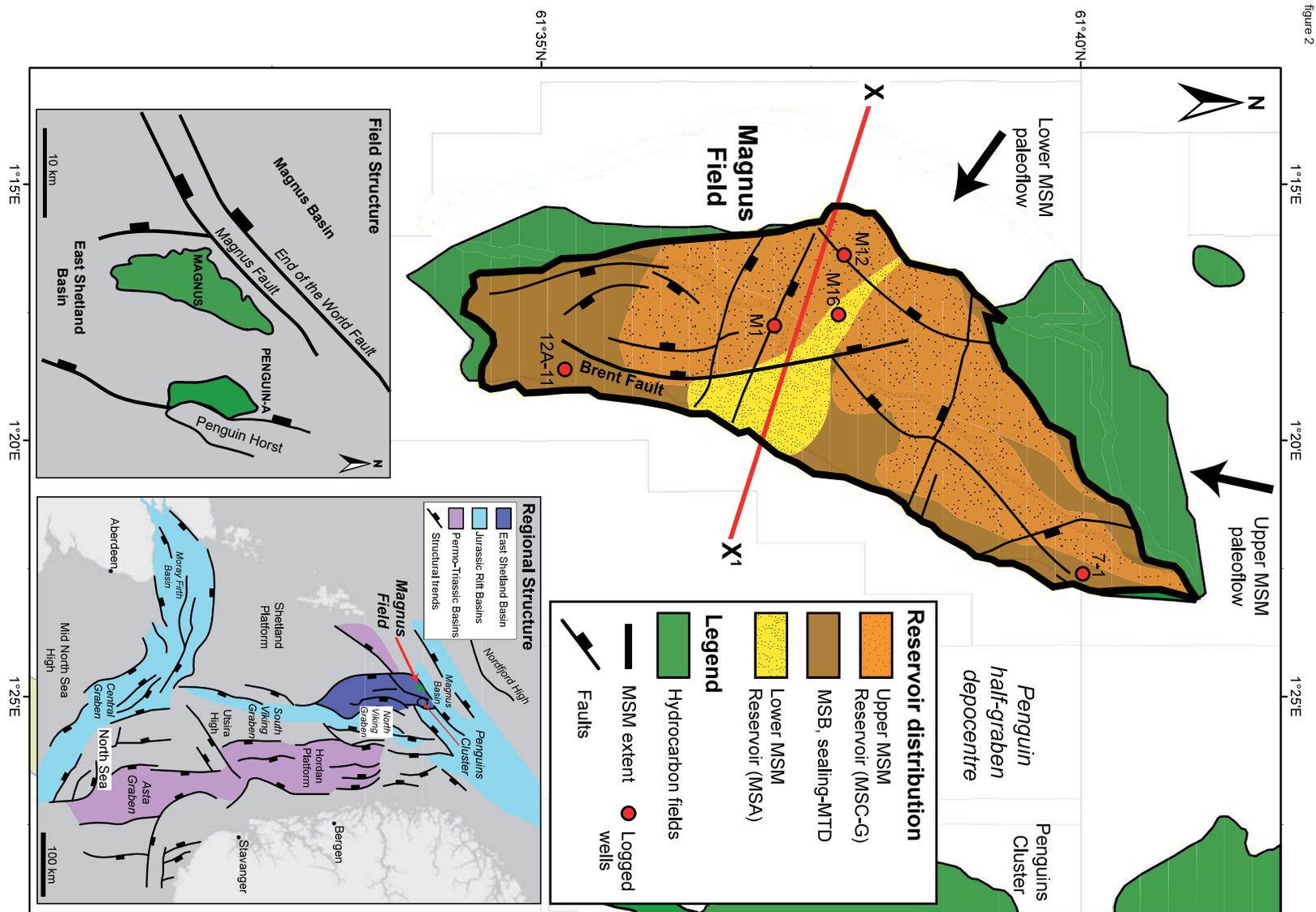


**(b) Strike section**



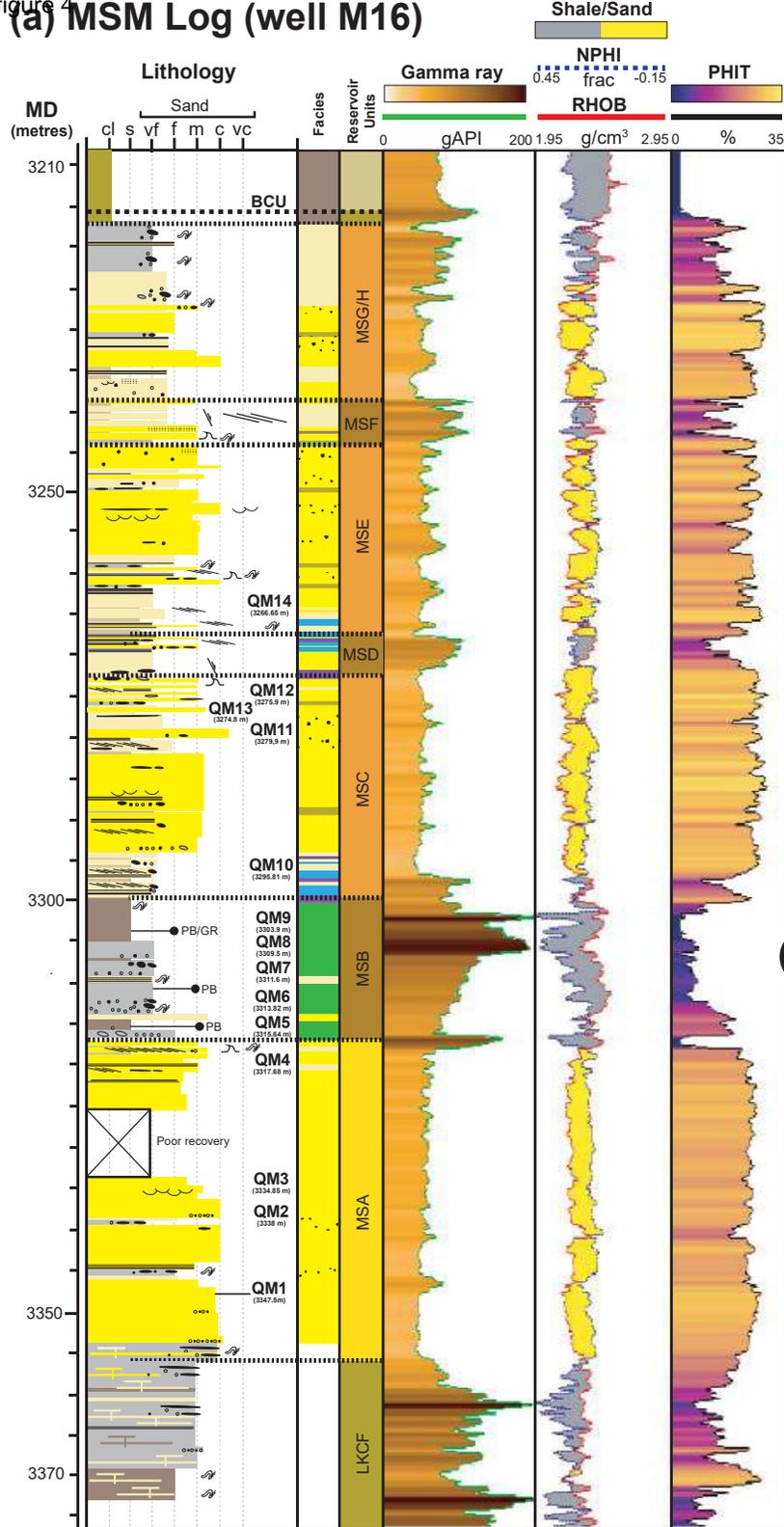
**(c) Idealised pressure and petrophysical response**



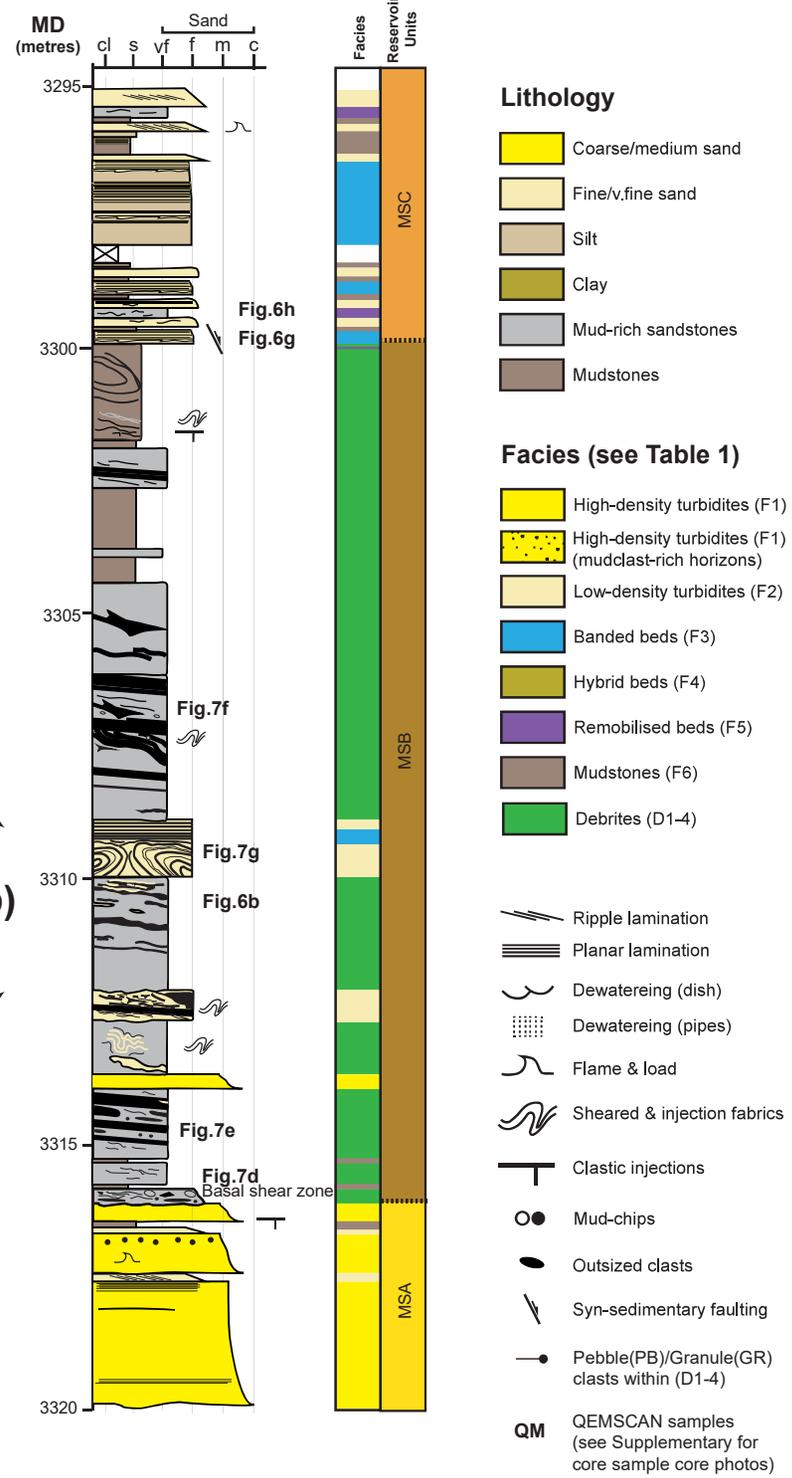


Jurassic						Cretaceous	Period	
Oxfordian	Kimmeridgian		Tithonian <i>Volgian Morris et al (1999)</i>			Berriasian	Epoch	
[Lithology patterns for Jurassic stages]						[Lithology pattern for Berriasian]	Lithology	
Heather Formation	Lower Kimmeridge Clay Formation (LKCF)		Lower MSM	MSB sealing-MTD	Upper Magnus Sandstone Member (MSM)	UKCF	Cromer Knoll Group	Litho-strat
	J56-2	J62	J63		J64	J66-70		Seq.Strat (J Seq)
Restricted Marin Shelf	Turbidite system + clastic injection				Sand-rich turbidite system	Hemipelagic	Shallow Marine	Depo Environment
<i>Early syn-rift (Late Bathonian-Oxfordian)</i>			<i>Uplif of Nordfjord high</i>			<i>Subsidence of Nordfjord high</i>		Tectonics
<i>Jurassic Late syn-rift</i>						<i>Early Cret. Rift (Mag &amp; EoW &amp; slumps)</i>		
Wells M12, M1, 7-1, 12A-11						Well M16	Stratigraphic distribution of core	

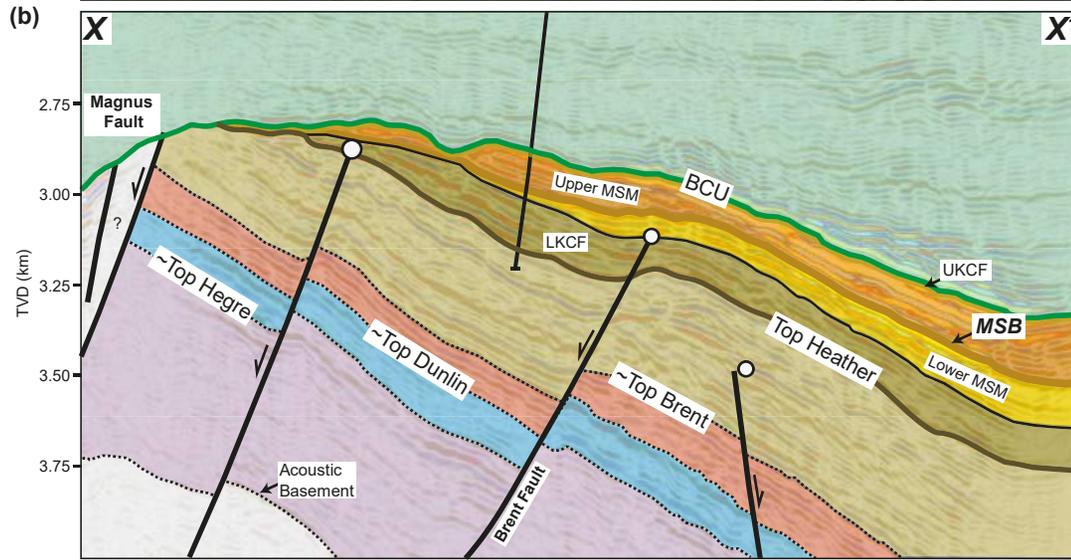
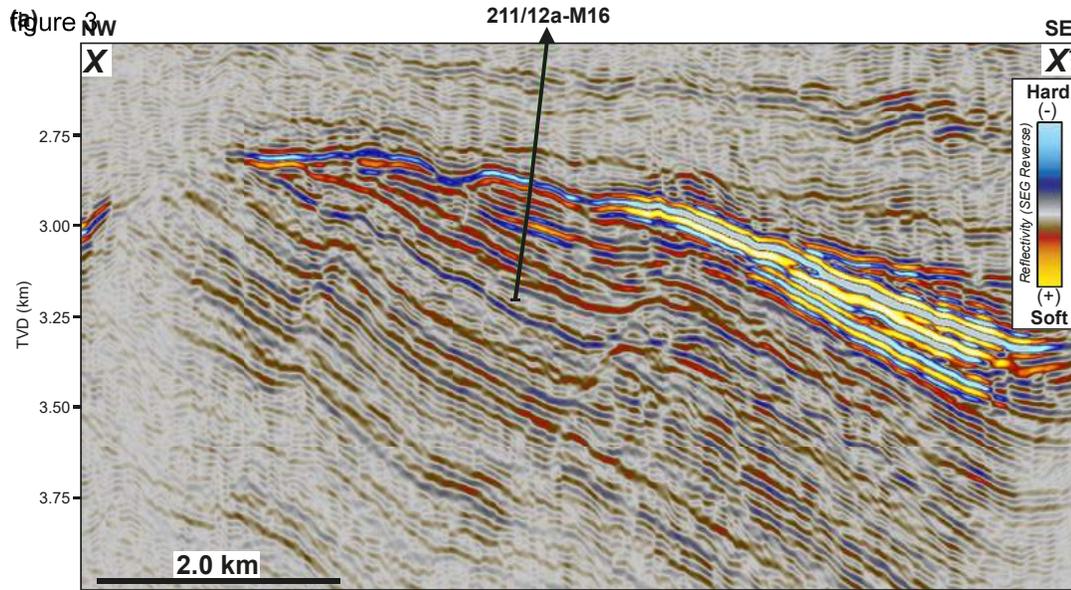
figure 4  
**(a) MSM Log (well M16)**



**(b) MTD Facies**



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[Click here to access/download;figure;Fig.3\\_reduced.pdf](#)

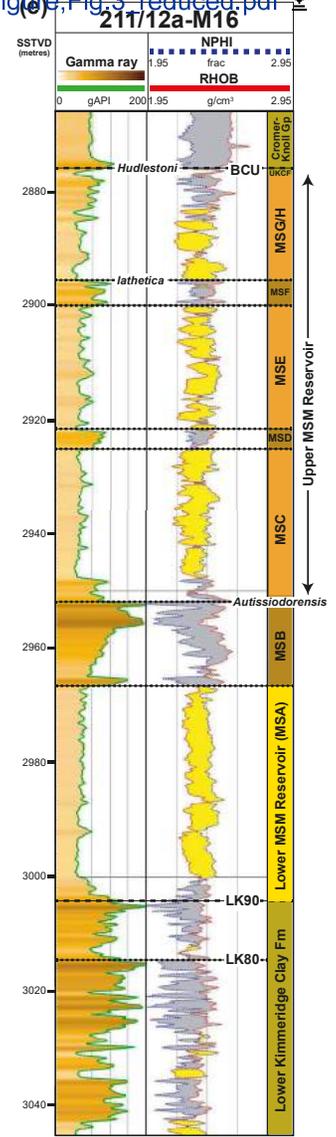
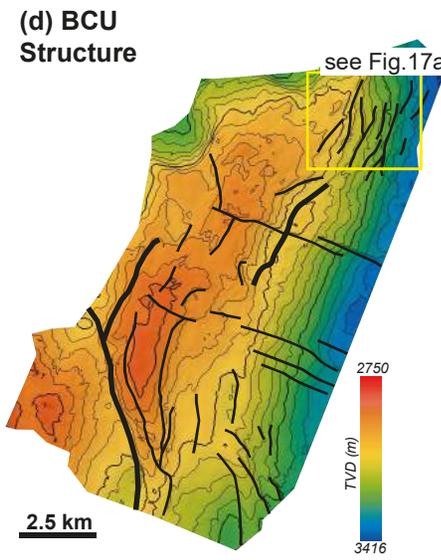
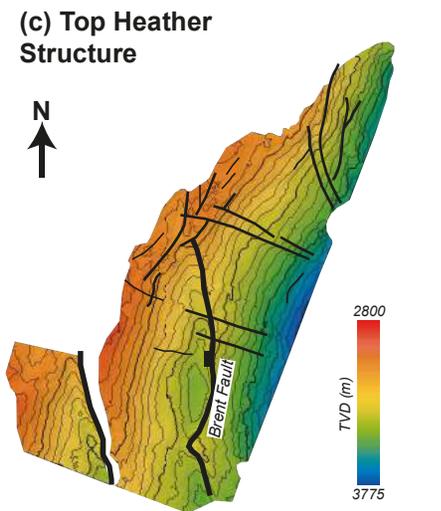


figure 5

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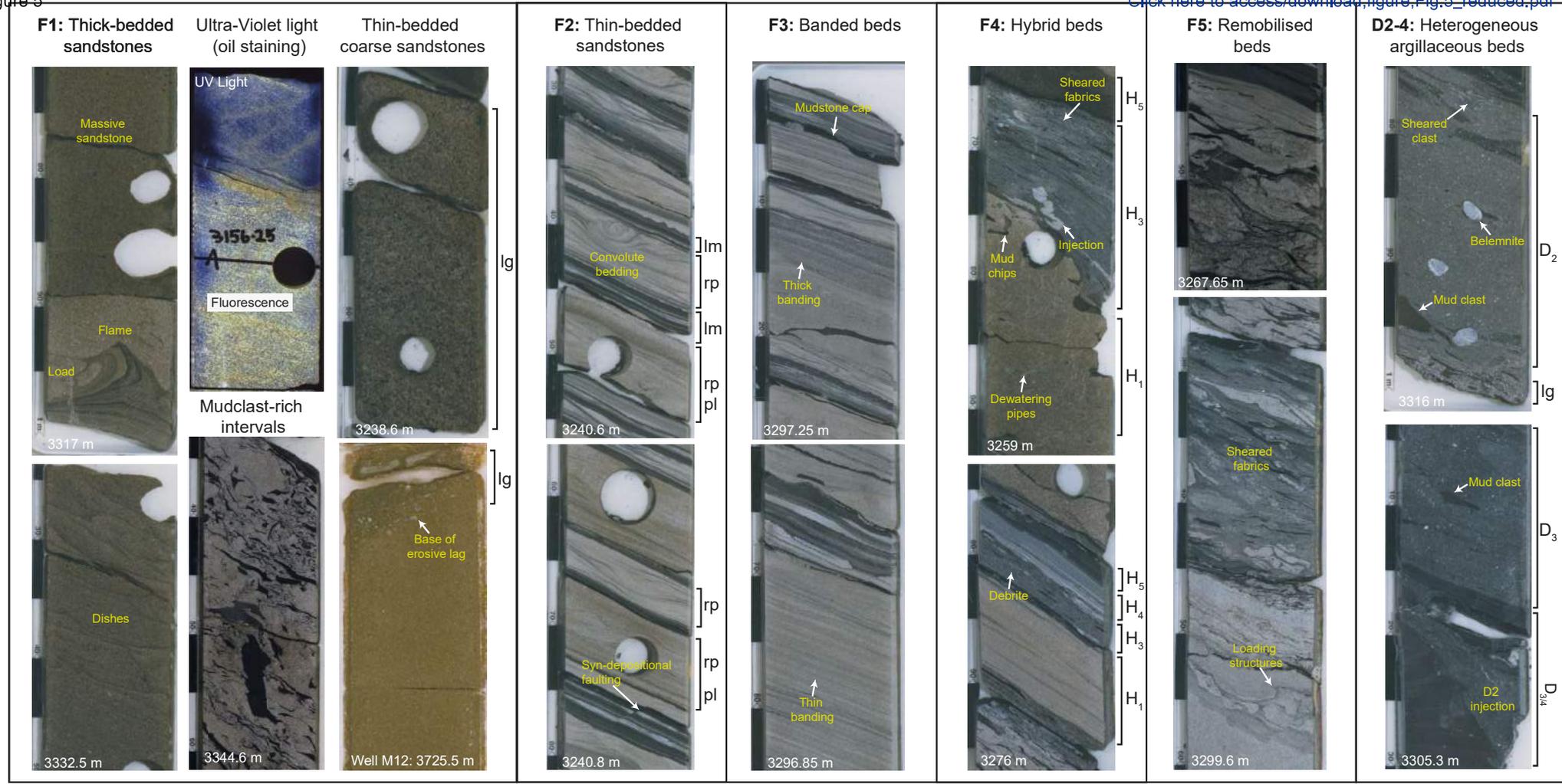
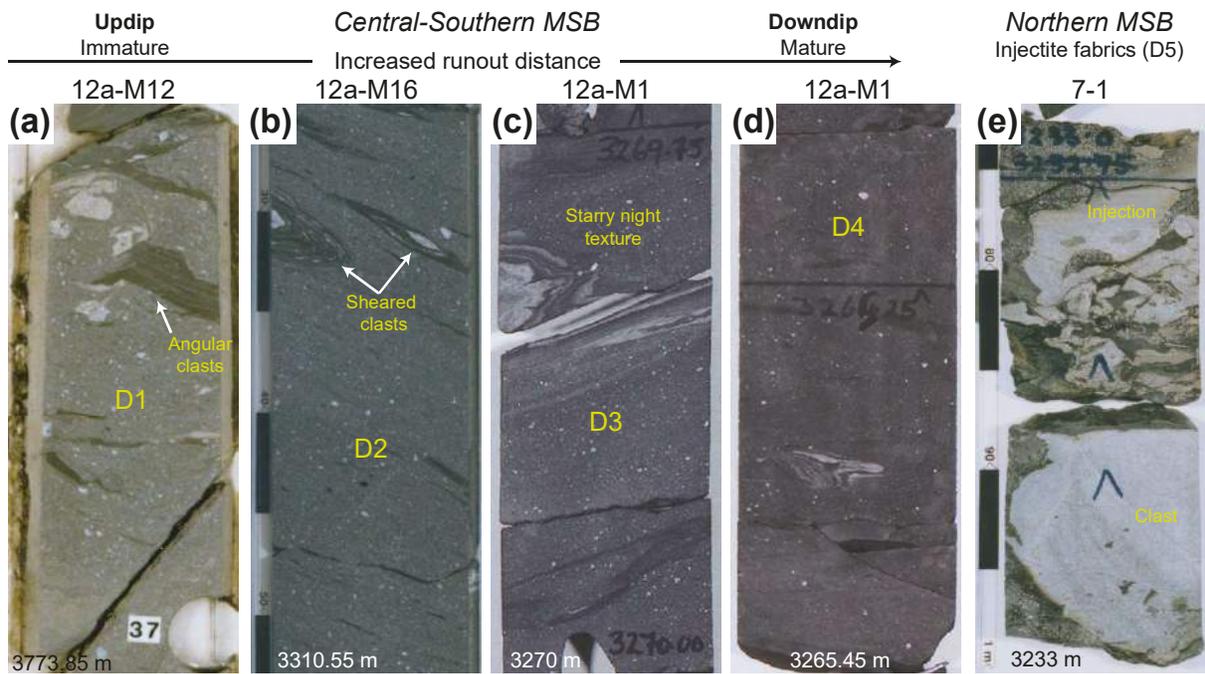


figure 6  
**Longitudinal flow transformation**

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**Transition from MSB to MSC**

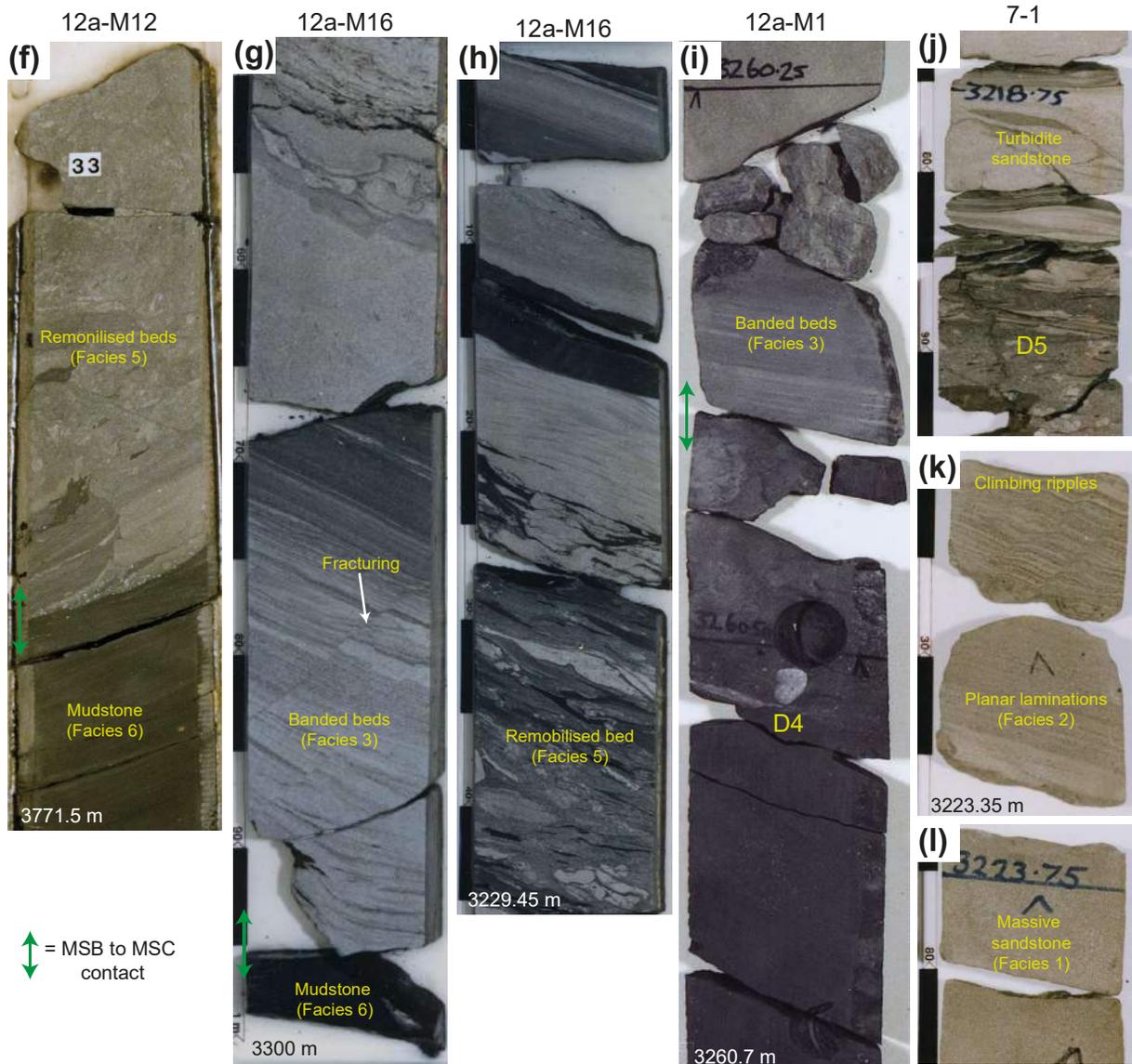
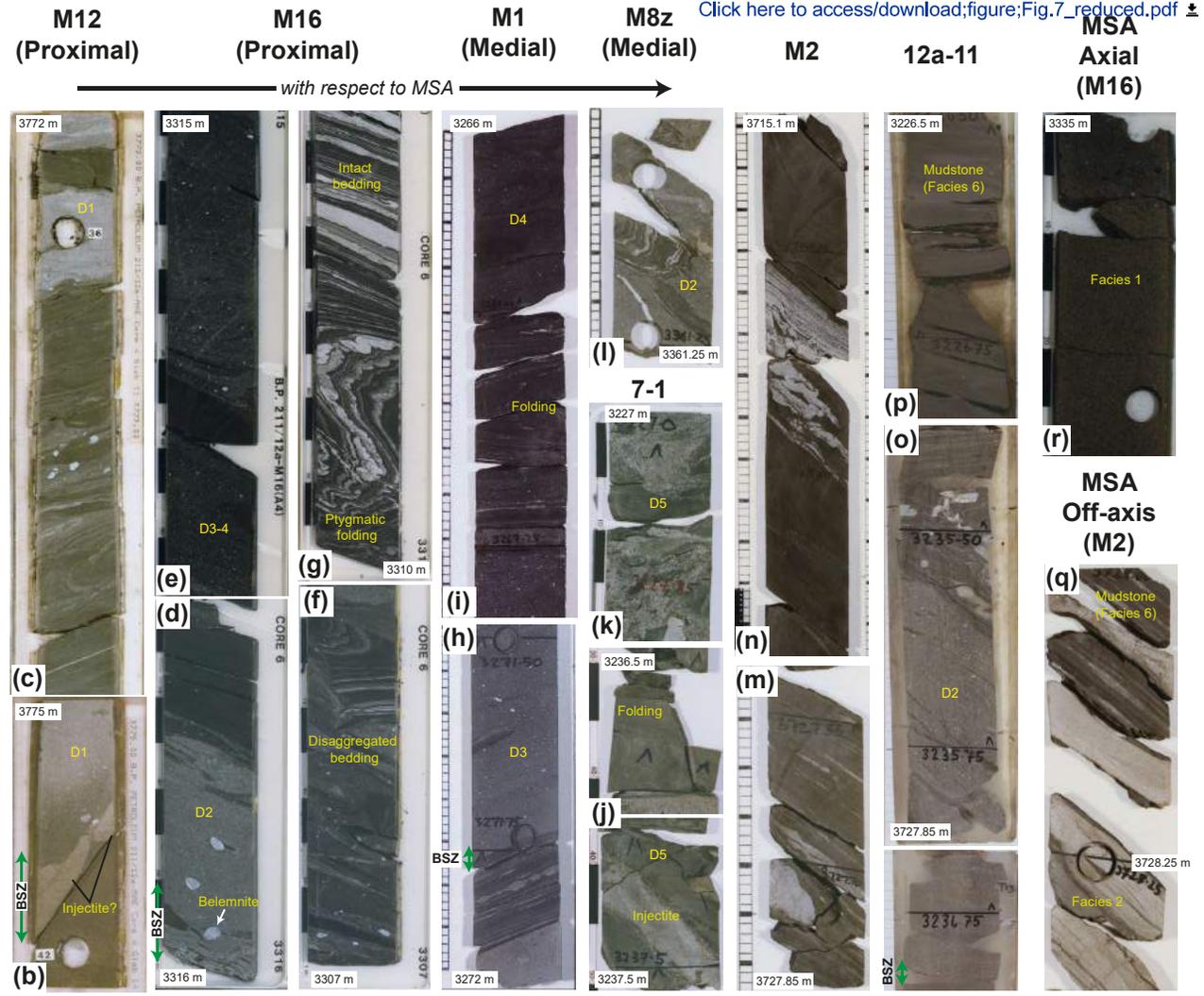
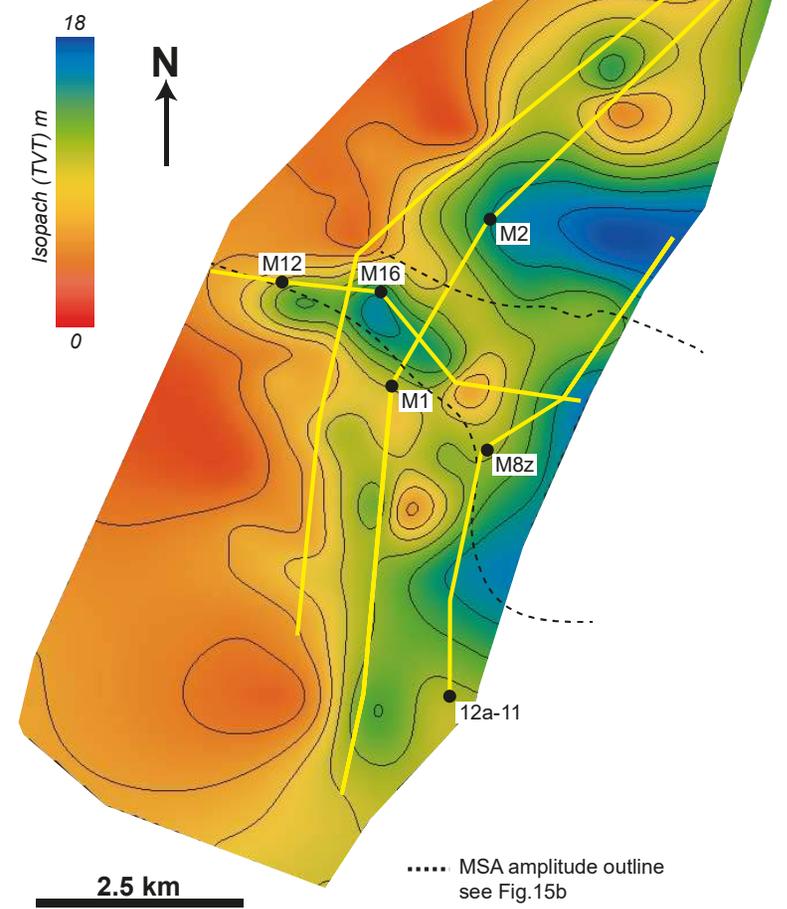


figure 7

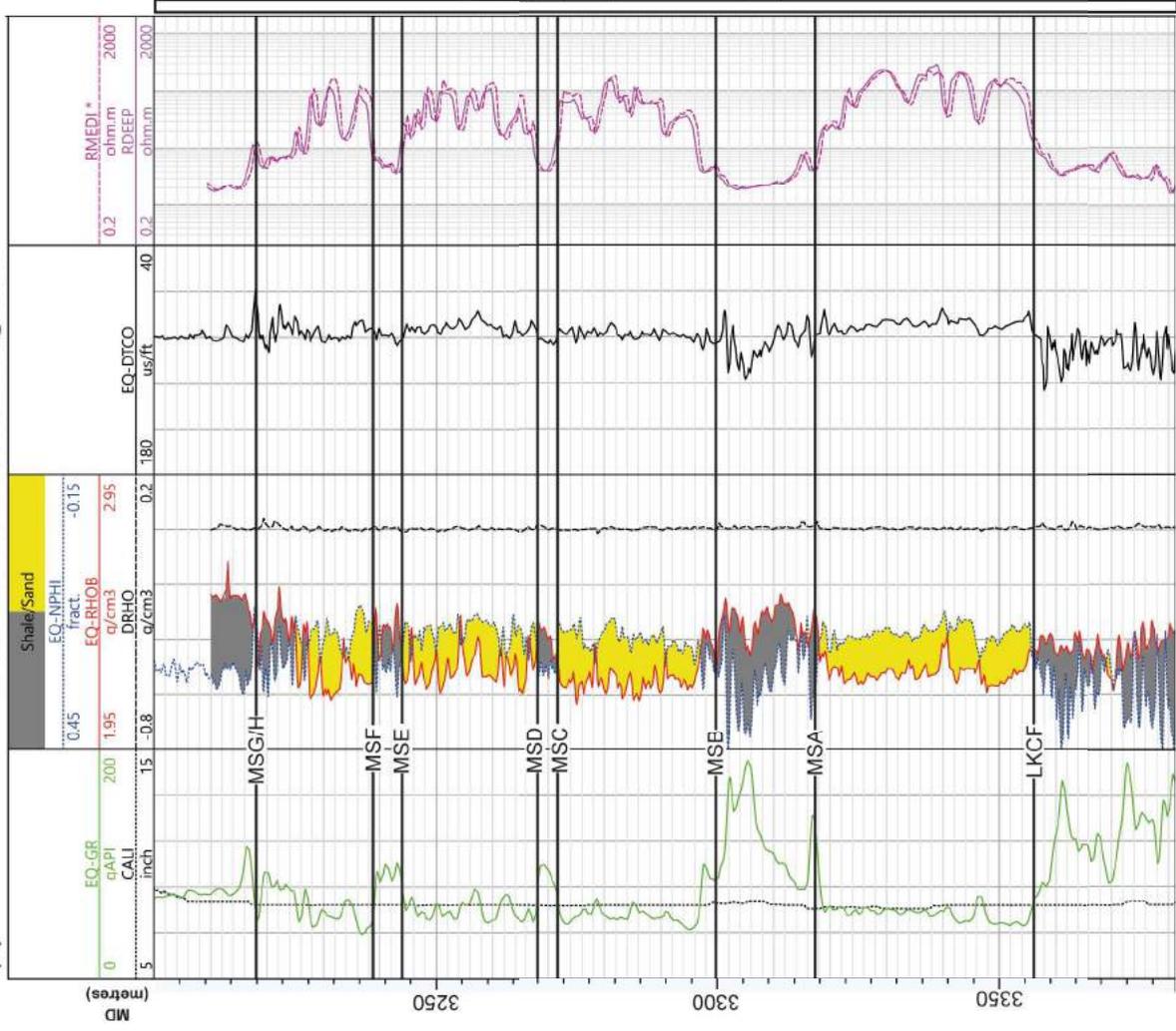
**(a) MSB Thickness**



[Click here to access/download;figure;Fig.7\\_reduced.pdf](#)

figure(a)

Well 2111/12a-M16: MSM log suite



(b) Click here to access/download;figure;Fig.8..pdf

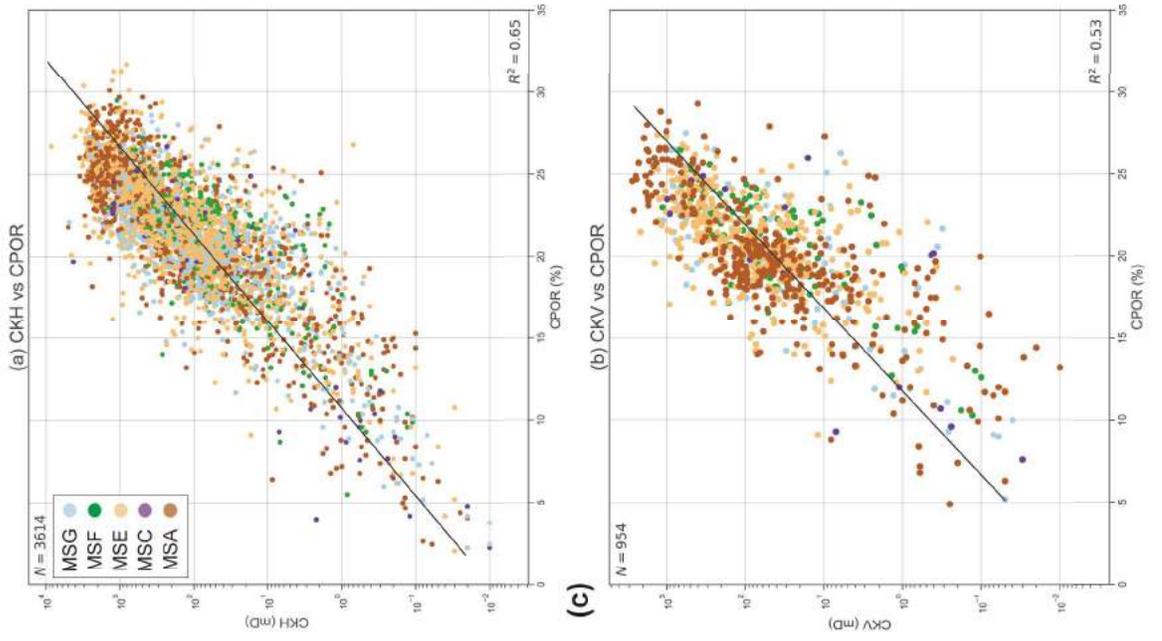
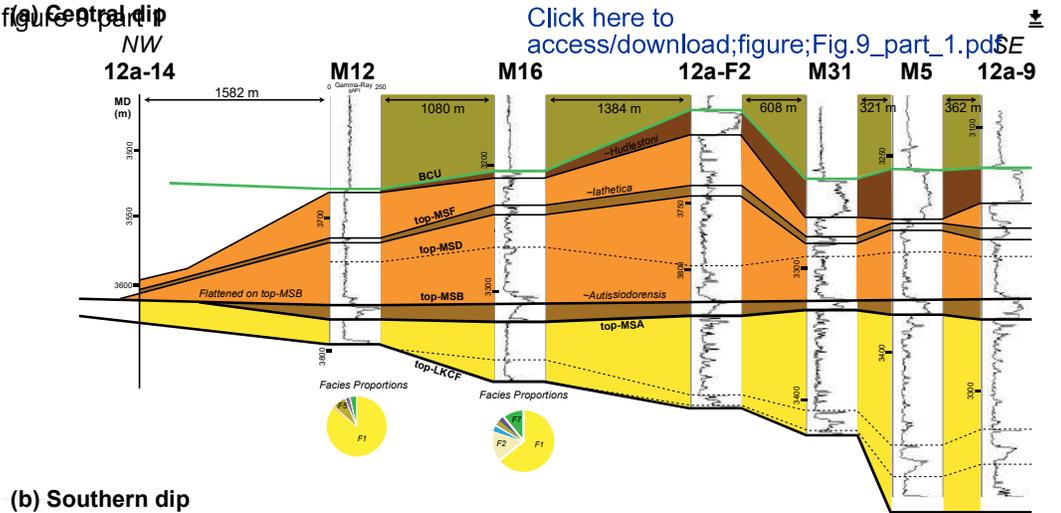
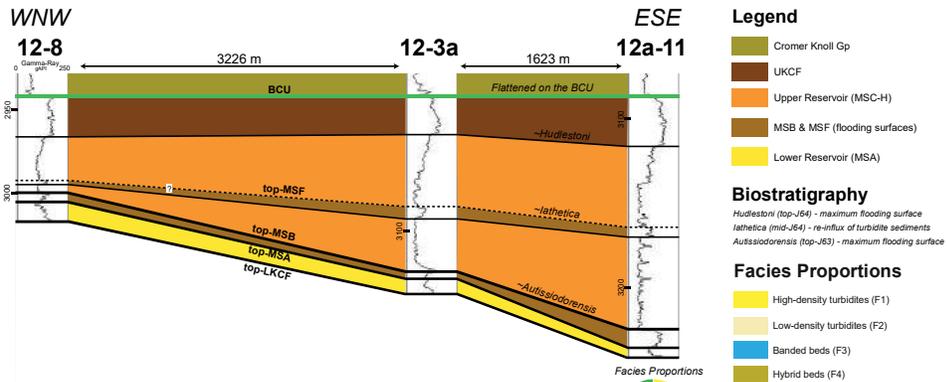


figure 9 part 1

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(b) Southern dip



(c) Northern dip

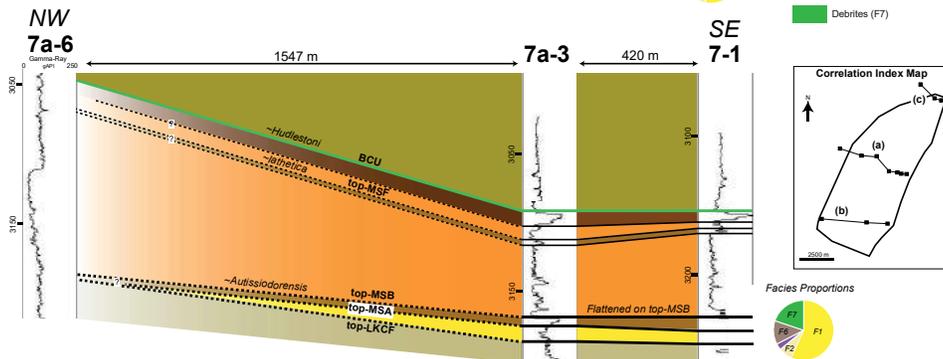
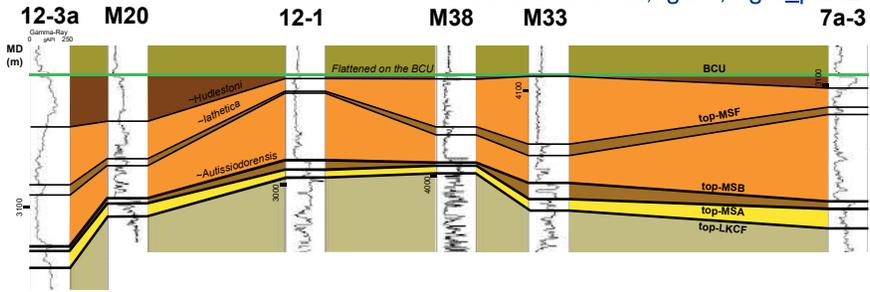
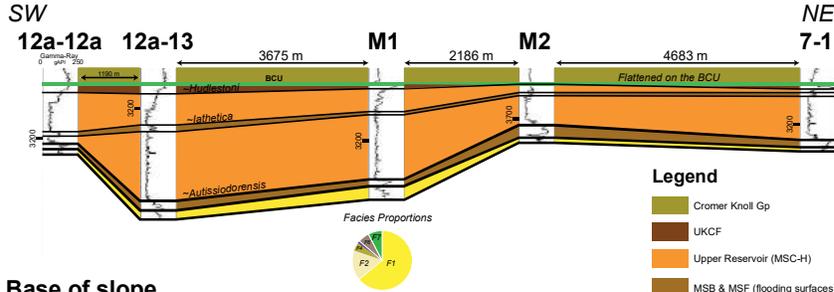


fig. 9 part 2  
Upper slope  
SW

Click here to  
access/download;figure;Fig.9 part 2  
NE



(e) Mid slope



- Legend**
- Cromer Knoll Gp
  - UKCF
  - Upper Reservoir (MSC-H)
  - MSB & MSF (flooding surfaces)
  - Lower Reservoir (MSA)

(f) Base of slope

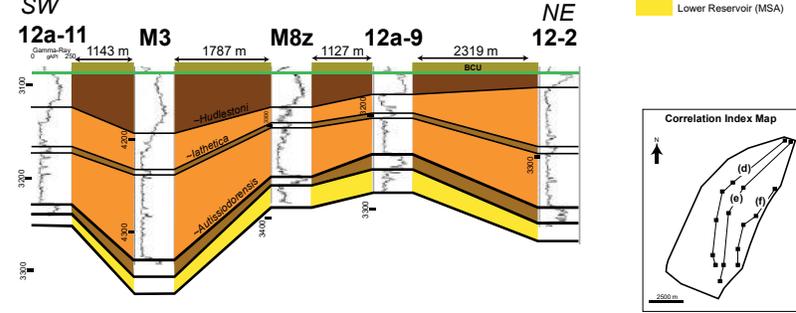
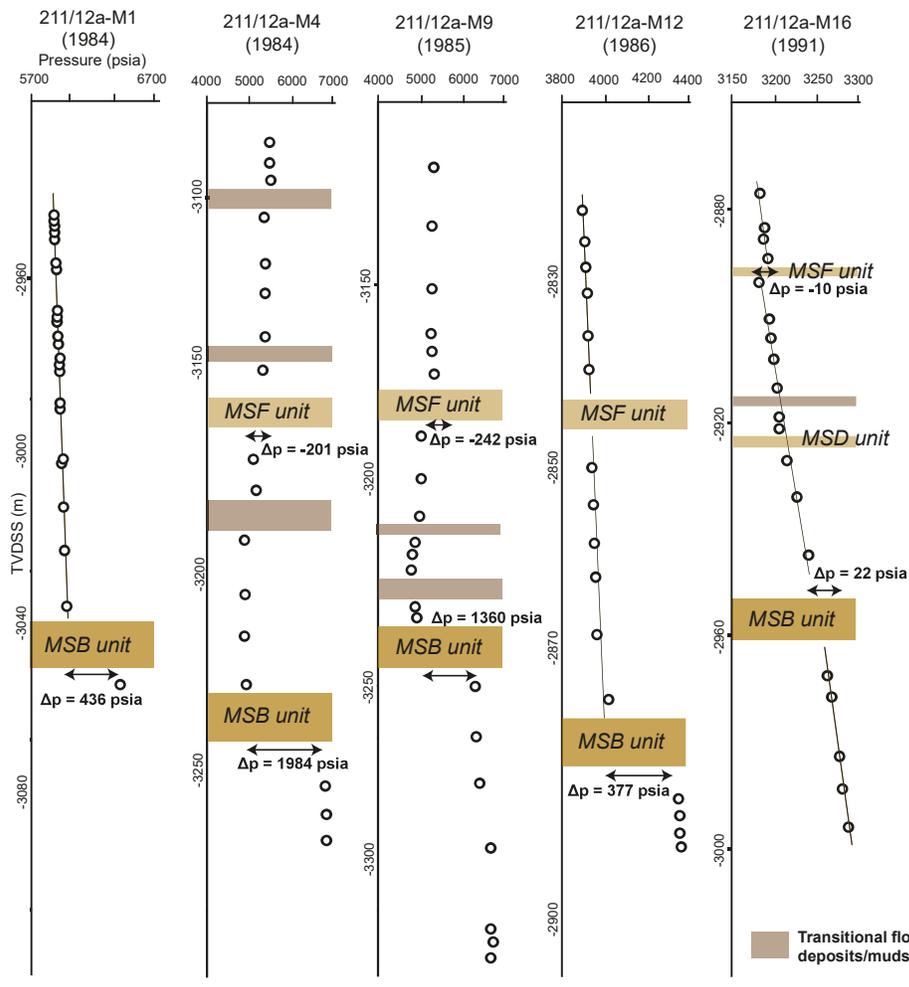
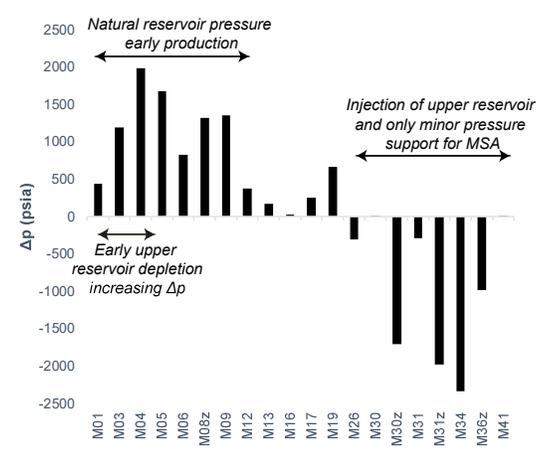


figure 10

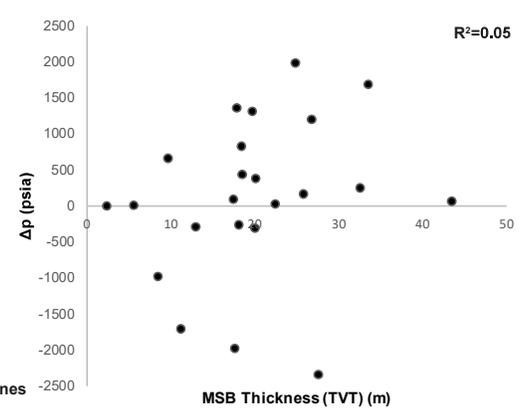
(a) Formation pressure plots



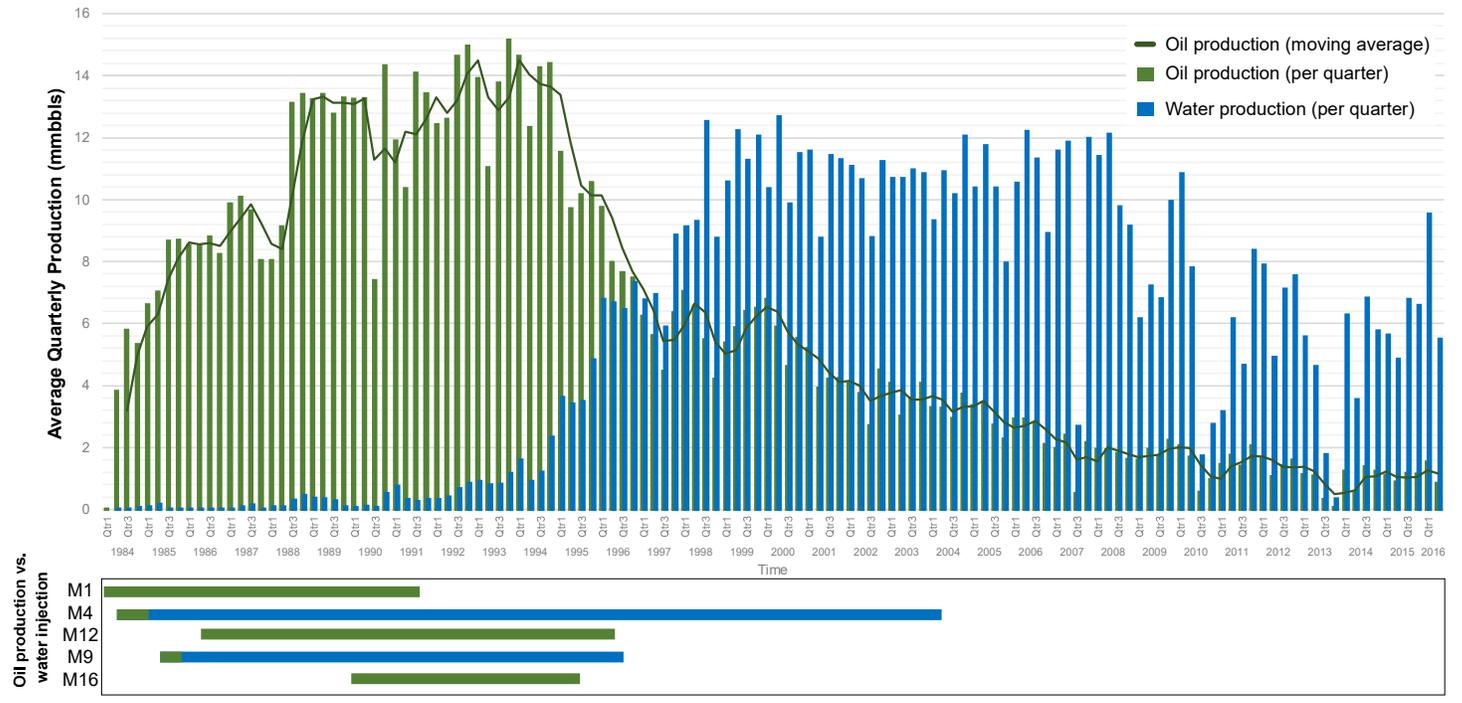
(b) Change in pressure between MSA-MSC

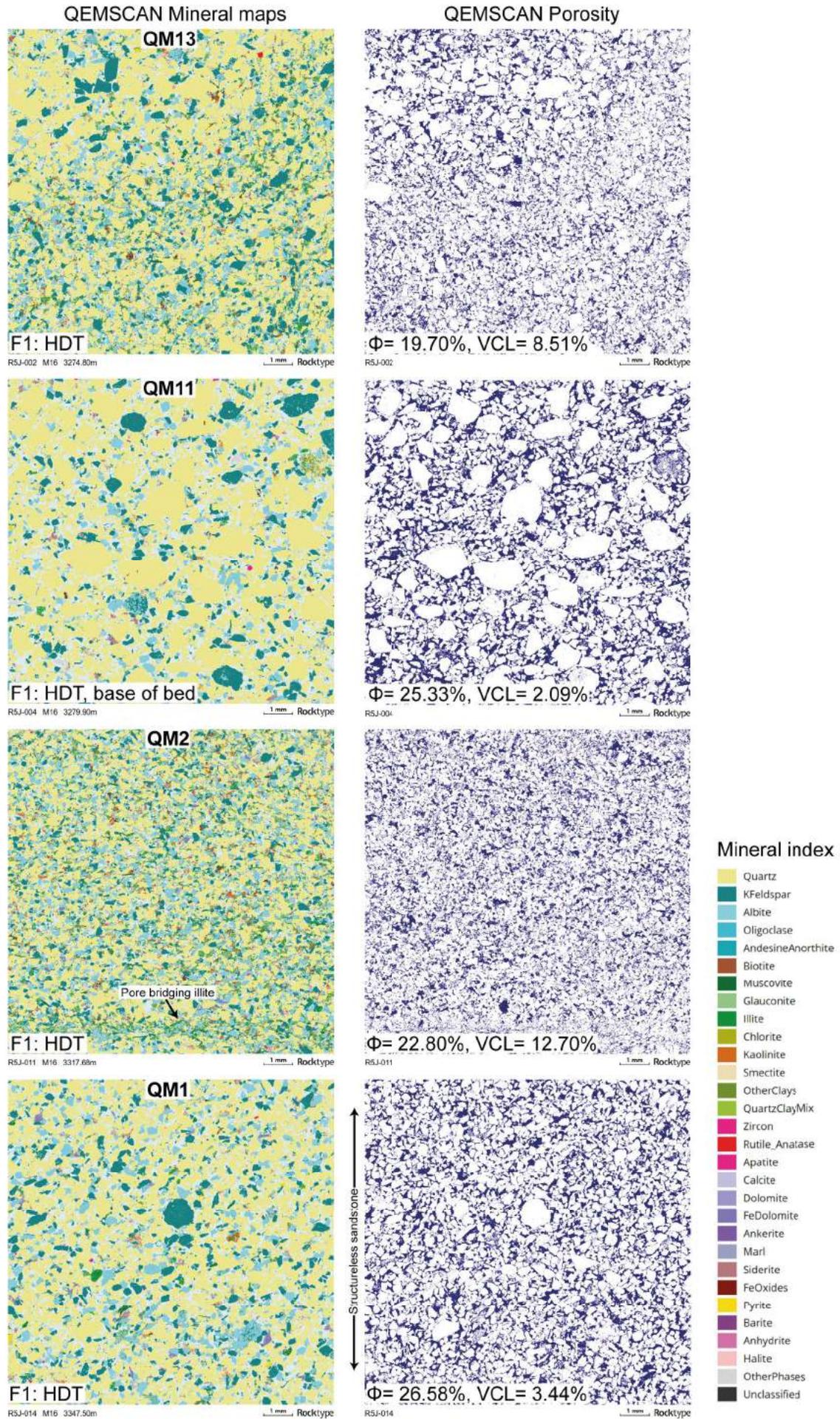


(c) Pressure vs MSB thickness



(d) Production history





# Laminar/Transitional Facies

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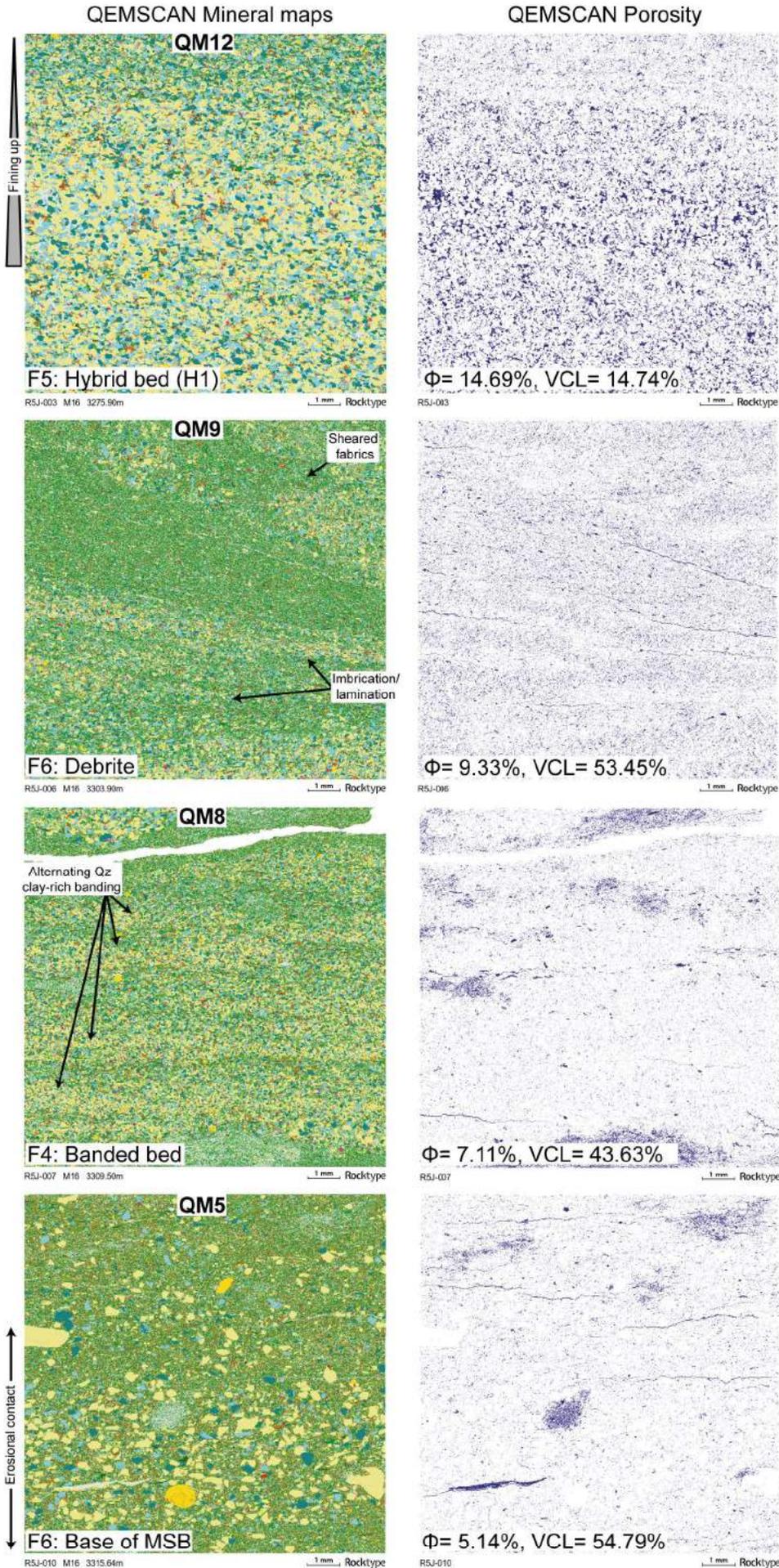


figure 13  
Grain Size Distribution

[Click here to access/download;figure;Fig.13.pdf](#)

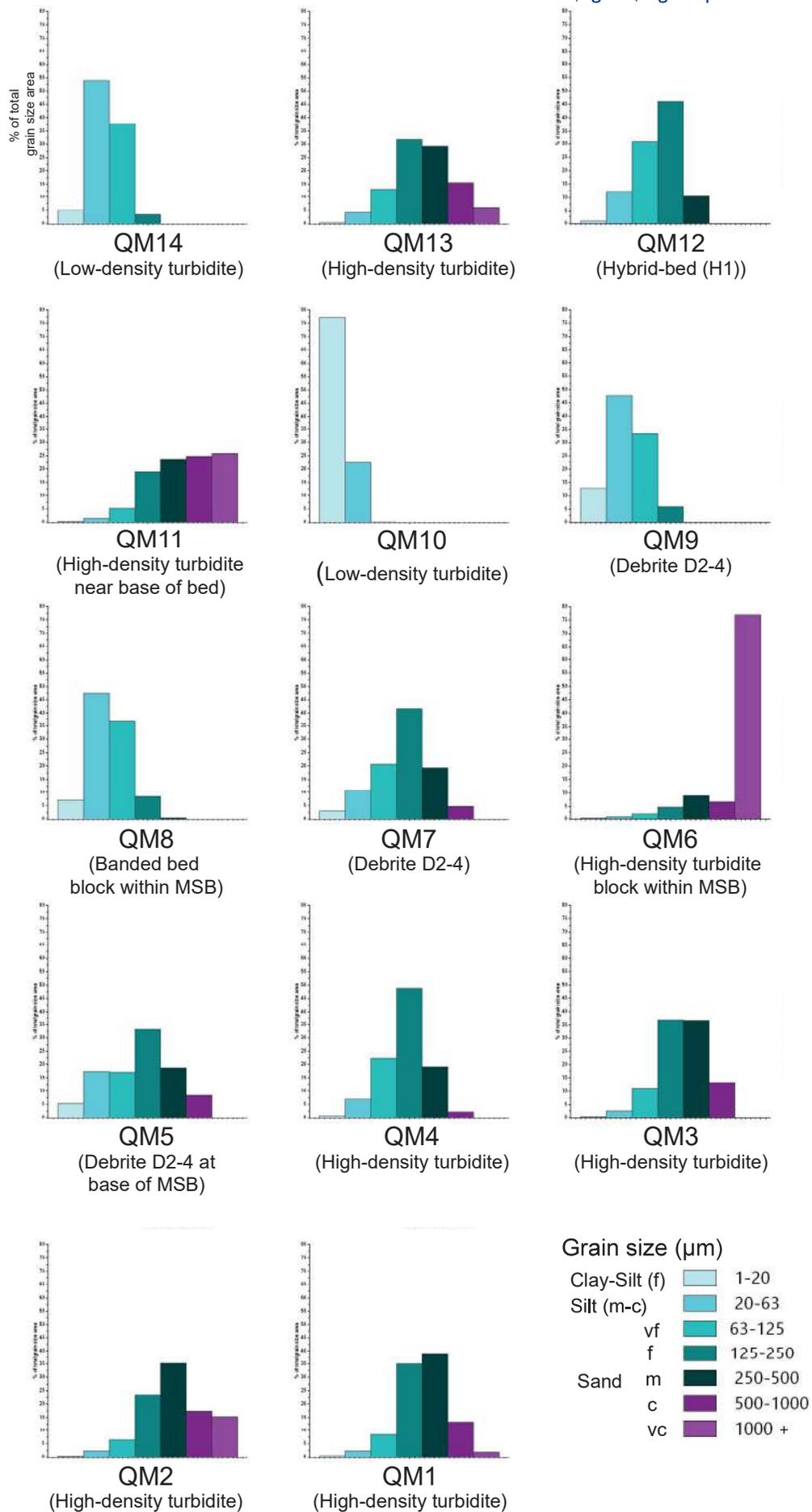
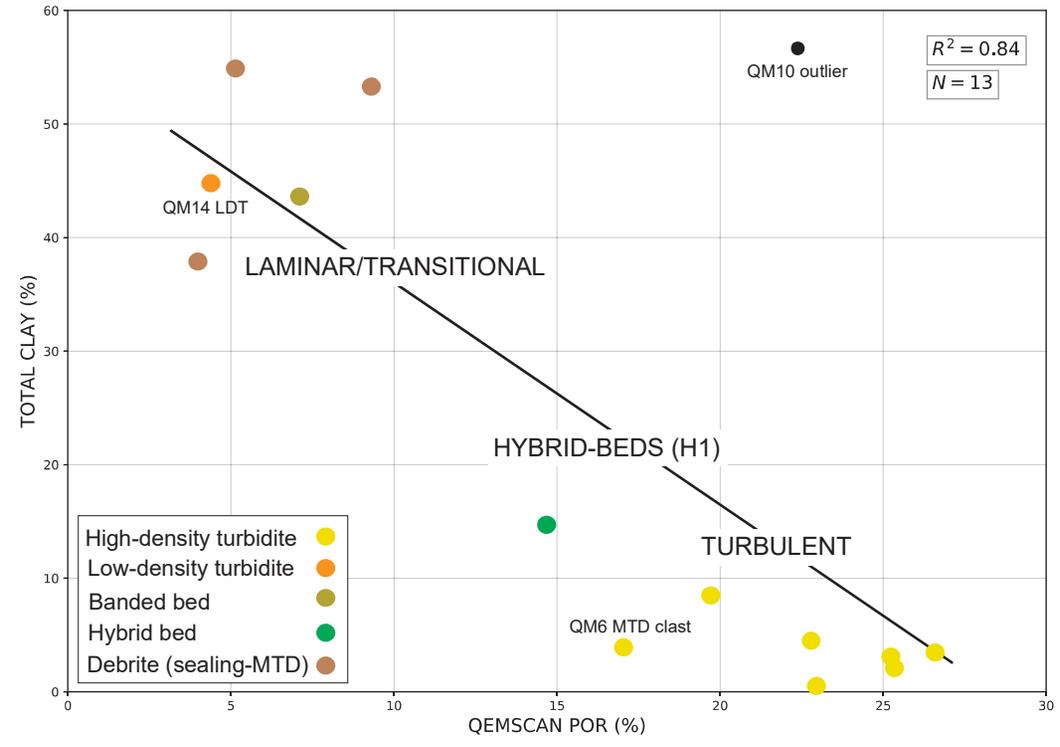


figure 14

(a) Total clay vs. porosity



(b) Ternary plot

[Click here to access/download;figure;Fig.14.pdf](#)

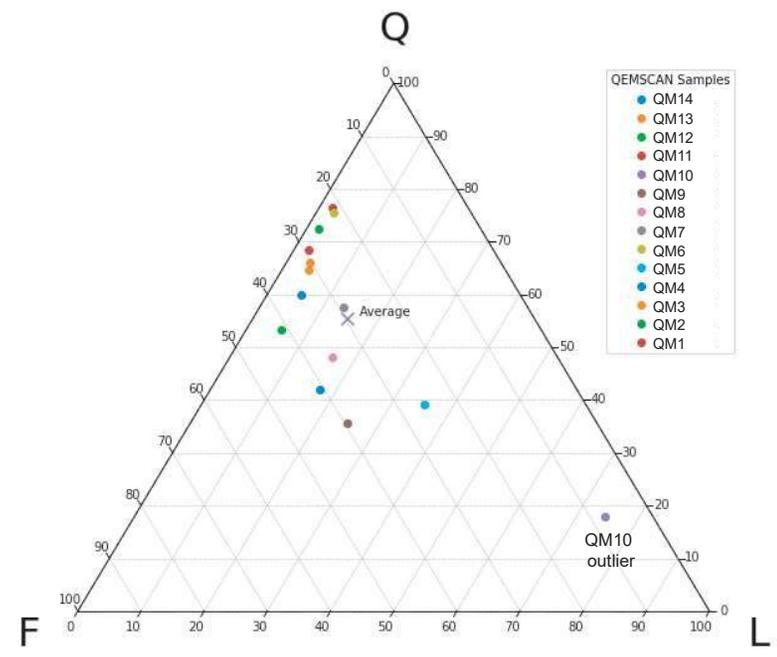


Figure 15

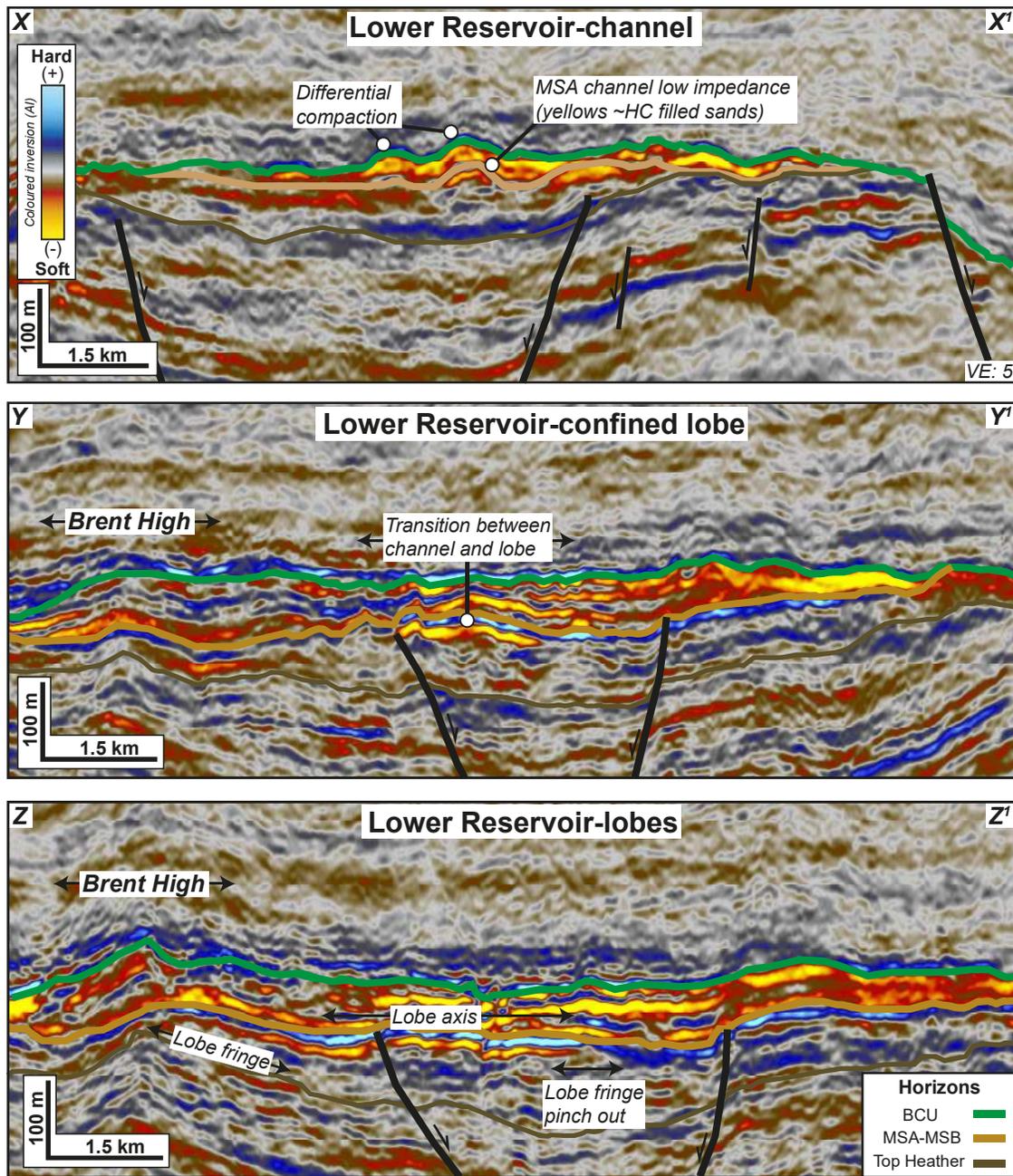
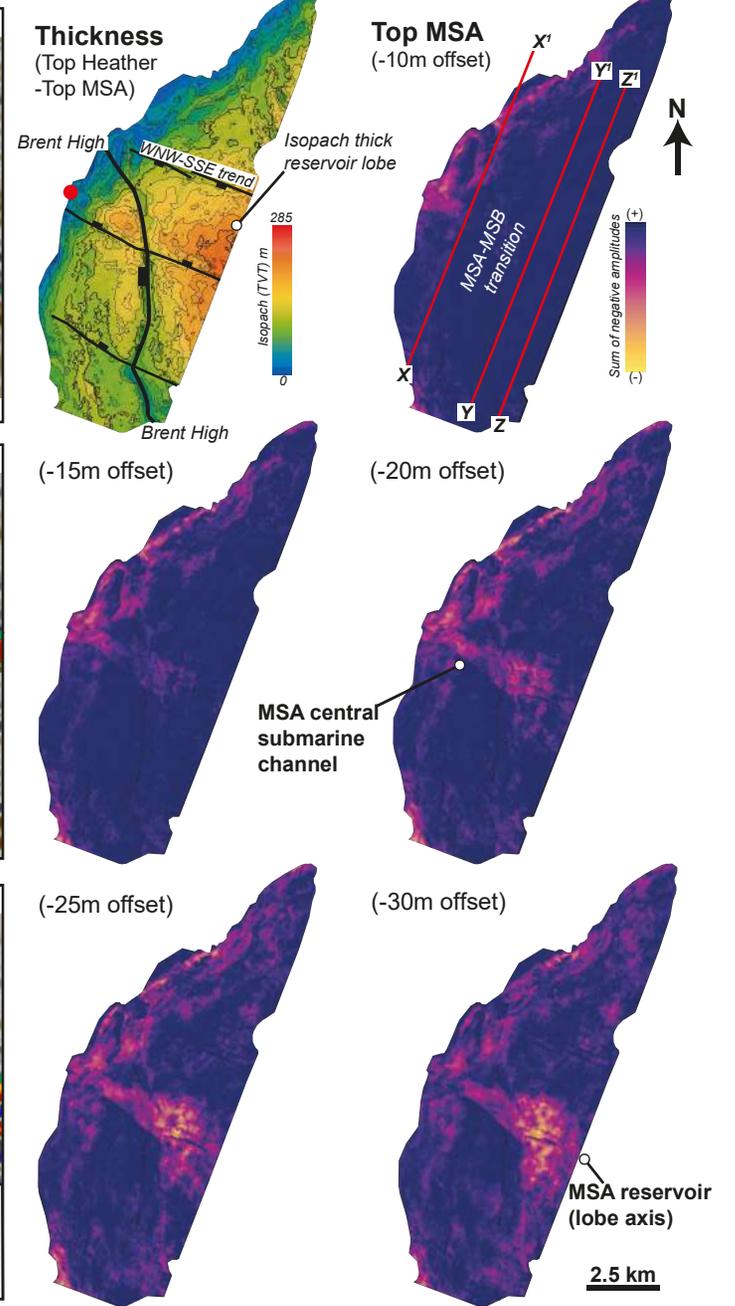
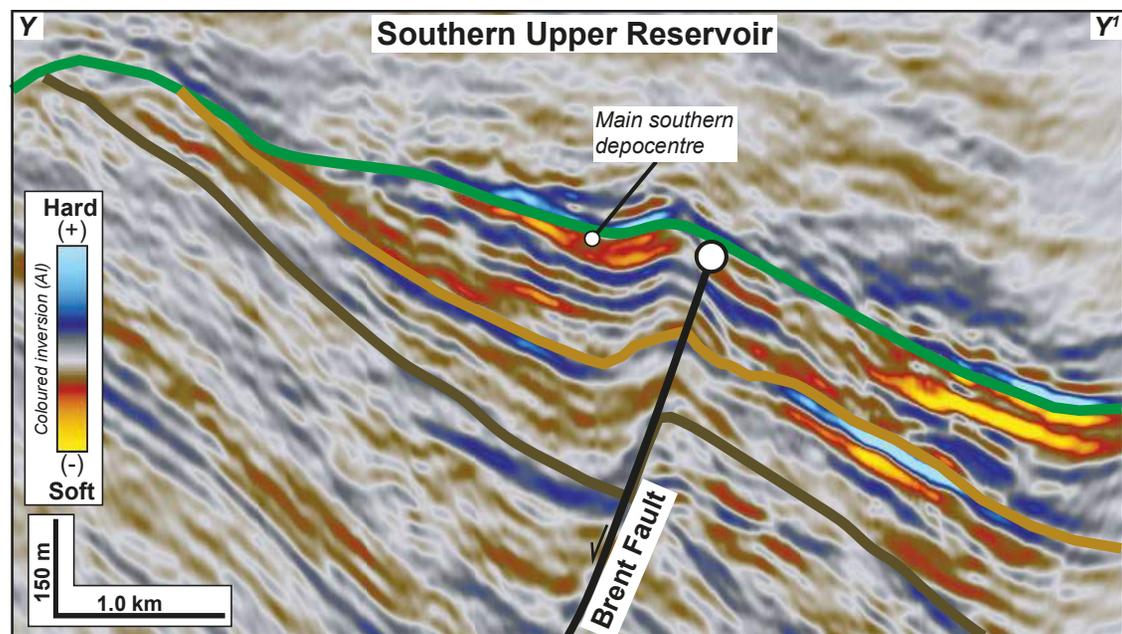
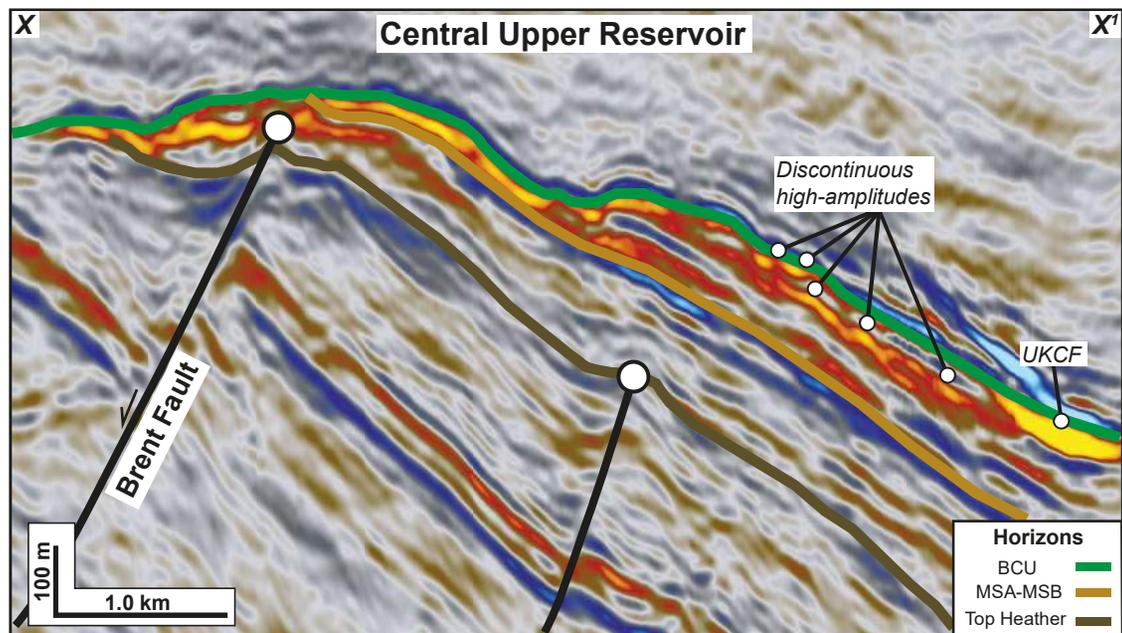


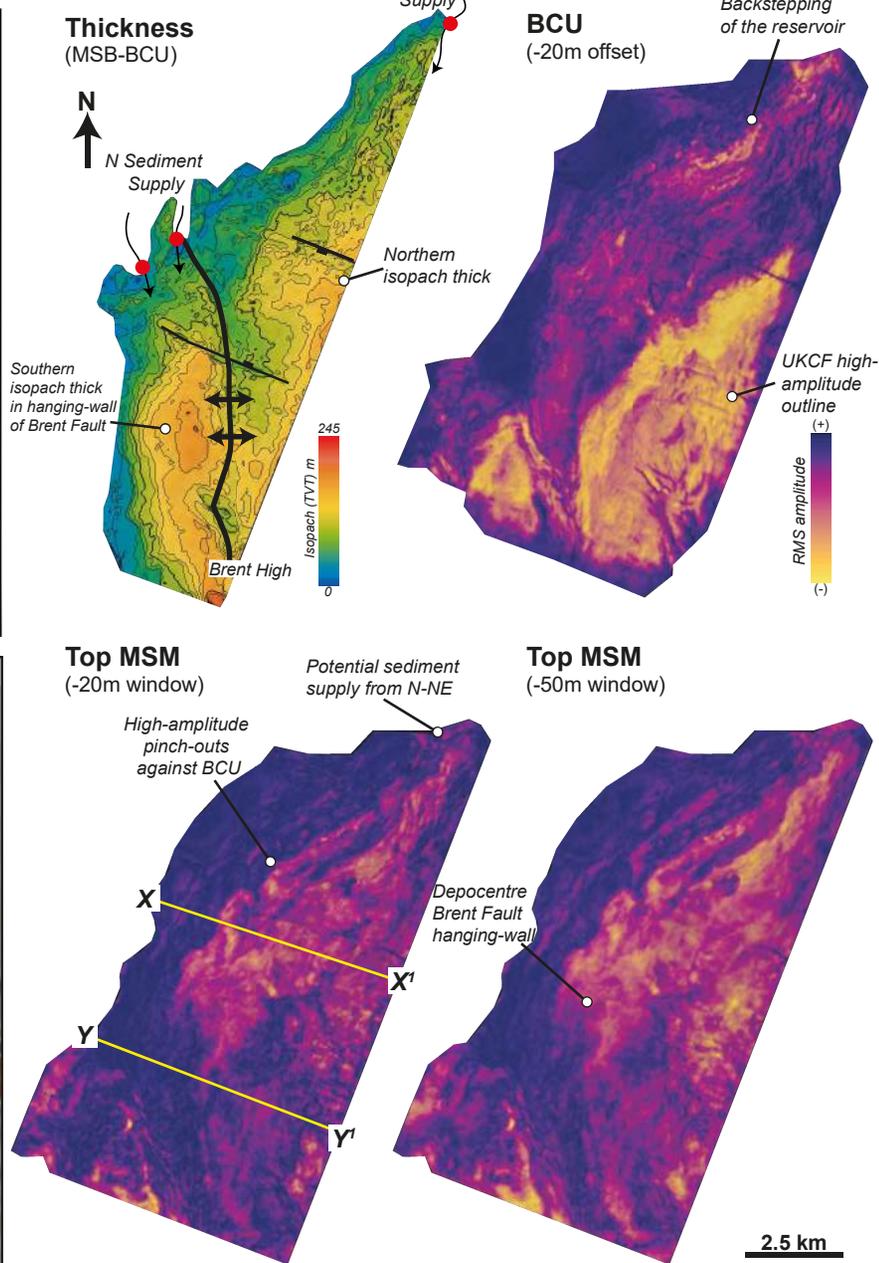
Figure 15 (continued)



(a) Figure 16

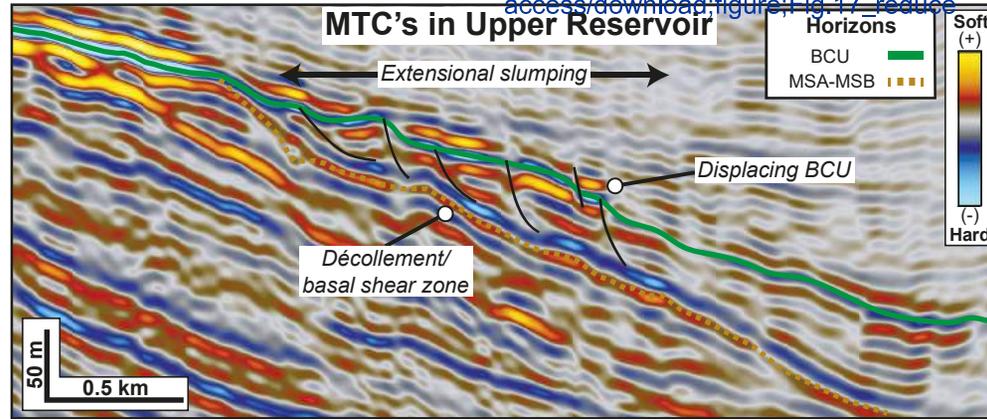


(b) [Click here to access/download;figure;Fig.16\\_reduced.pdf](#)

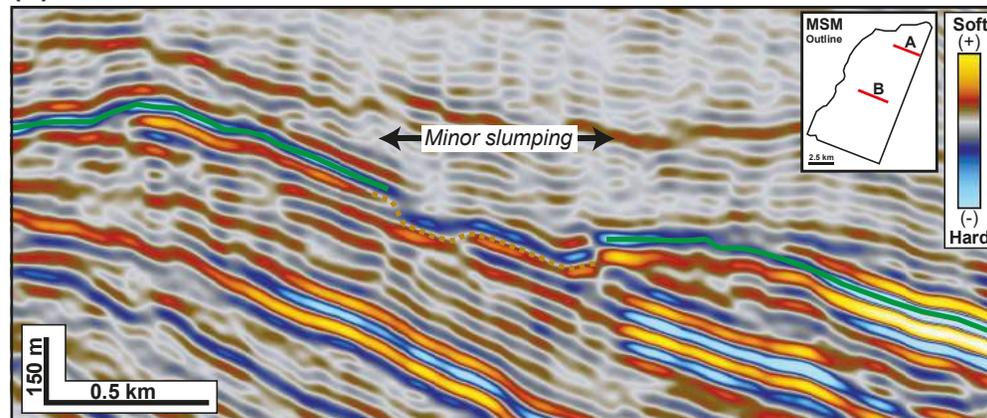


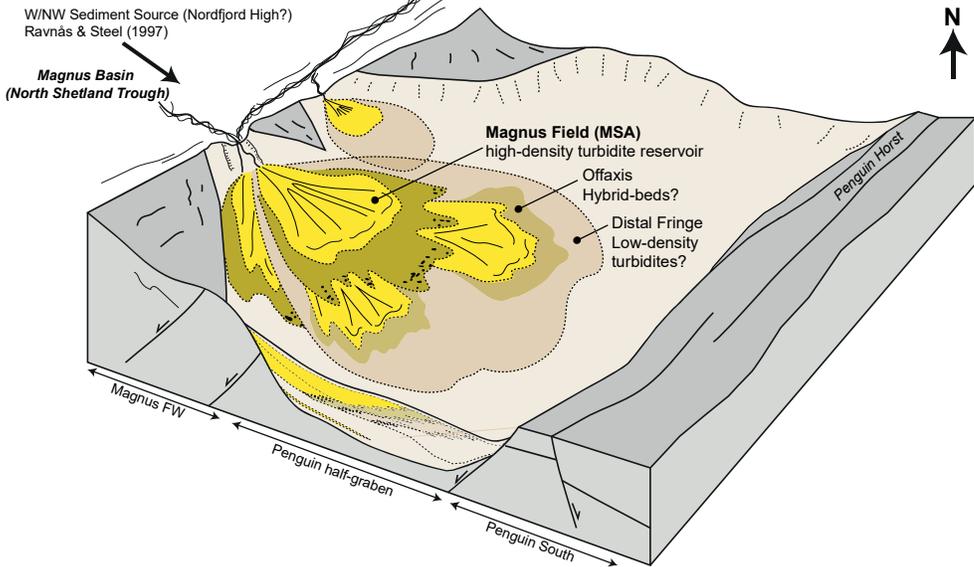
(a) re 17

[Click here to access/download:figure, Fig.17\\_reduced](#)

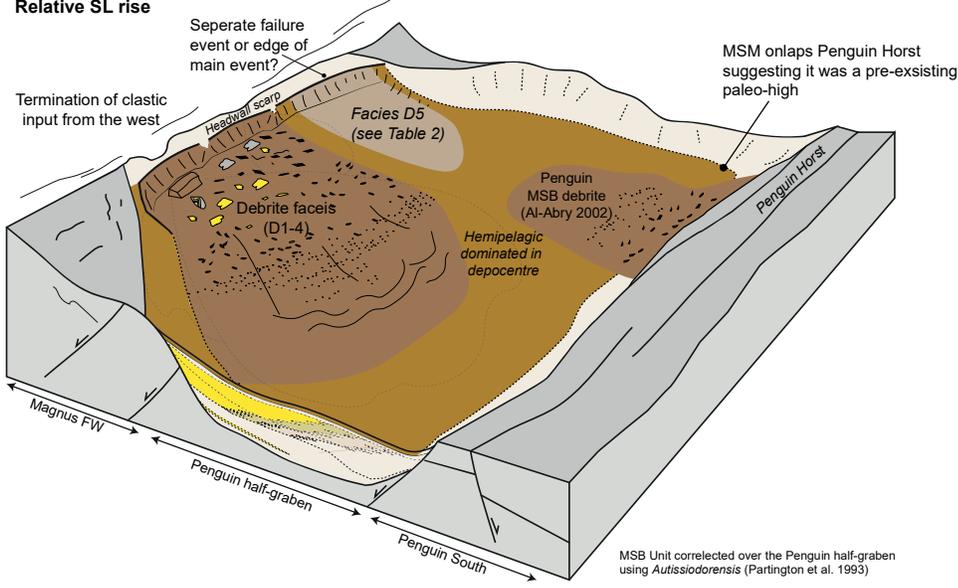


(b)

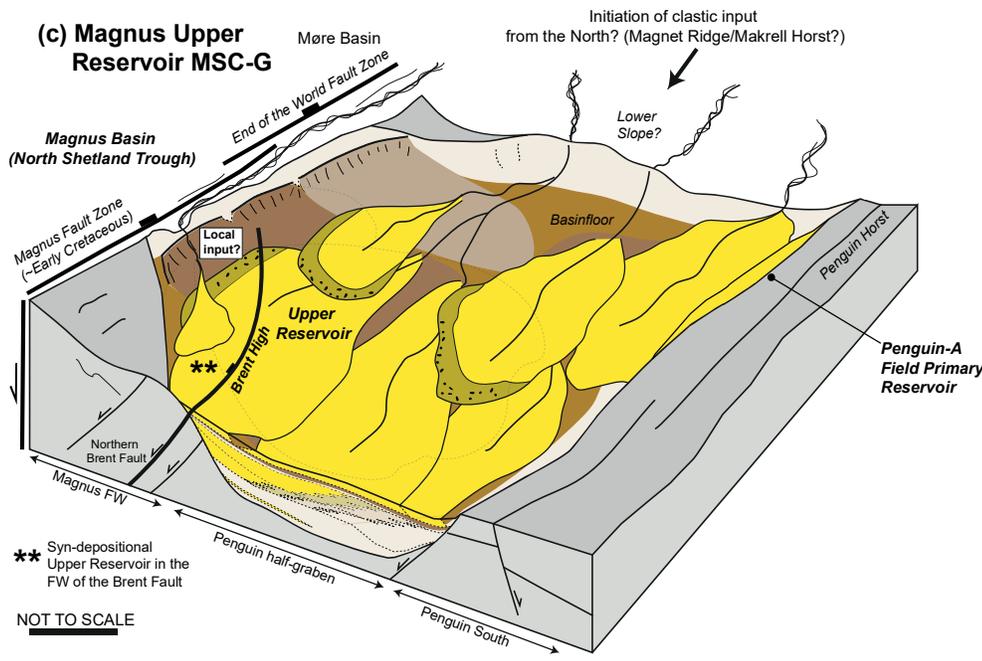




**(b) Intra-MTD**  
Tectonic Instability, Subsidence  
Relative SL rise



**(c) Magnus Upper Reservoir MSC-G**



\*\* Syn-depositional Upper Reservoir in the FW of the Brent Fault

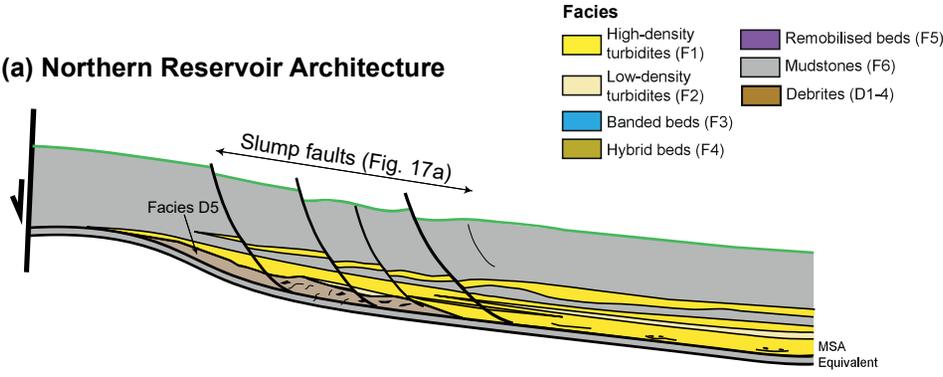
**NOT TO SCALE**

figure 19

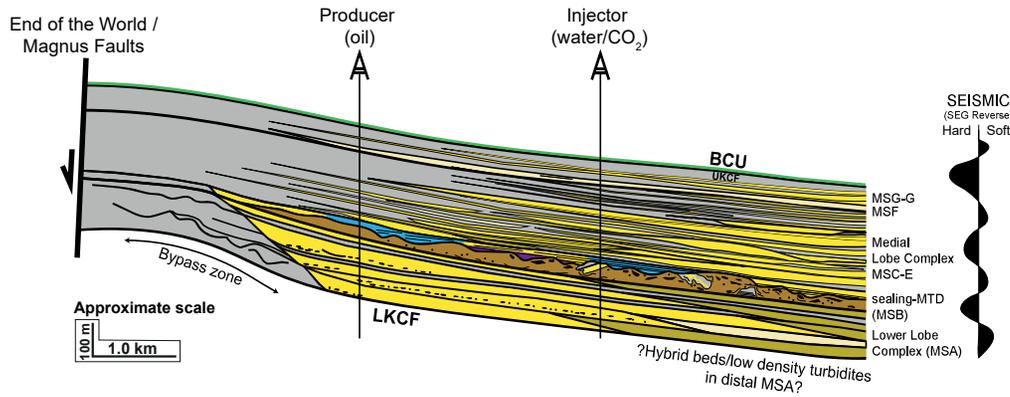
# Reservoir Architecture Synthesis

[Click here to access/download;figure;Fig.19.pdf](#)

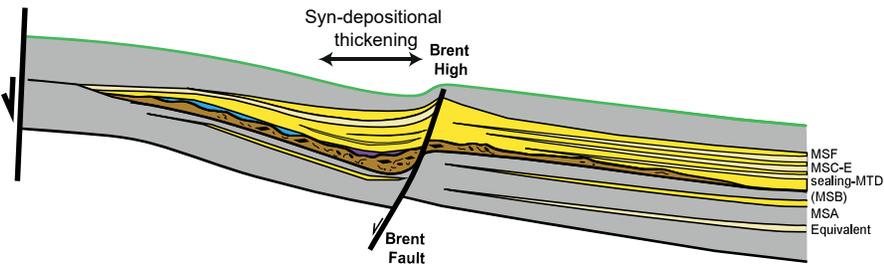
## (a) Northern Reservoir Architecture



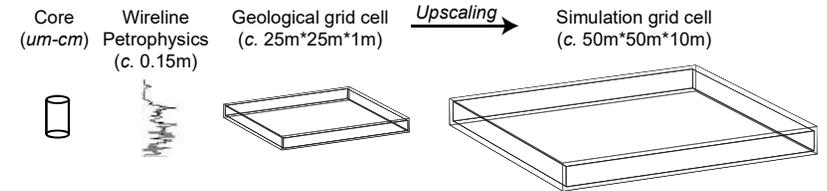
## (b) Central Reservoir Architecture



## (c) Southern Reservoir Architecture

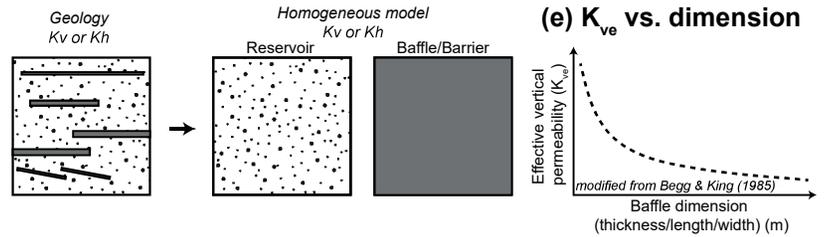


## (d) Heterogeneity and scale



\*Note each grid cell can only be assigned one value of  $\Phi$ ,  $K_v$ ,  $K_h$ , Facies

### Baffles representation in grid cell



## (f) Reservoir heterogeneity summary

