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Article:

1   **FRONTAL AND LATERAL SUBMARINE LOBE FRINGES: COMPARING SEDIMENTARY FACIES,**

2   **ARCHITECTURE AND FLOW PROCESSES**

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12

13   **ABSTRACT**

14   Submarine lobe fringe deposits form heterolithic successions that may include a high proportion of

15   hybrid beds. The identification of lobe fringe successions aids interpretation of paleogeographic

16   setting and the degree of basin confinement. Here, for the first time, the sedimentological and

17   architectural differences between frontal and lateral lobe fringe deposits are investigated. Extensive

18   outcrop and core data from Fan 4, Skoorsteenberg Formation, Karoo Basin, South Africa, allow the

19   rates and style of facies changes from axis to fringe settings of lobes and lobe complexes in both

20   down-dip (frontal) and across-strike (lateral) directions to be tightly constrained over a 800 km^2

21   study area. Fan 4 comprises three sand-prone divisions that form compensationally stacked lobe

22   complexes, separated by thick packages of thin-bedded siltstone and sandstone intercalated with

23 (muddy) siltstone, interpreted as the fringes of lobe complexes. Lobe-fringe facies associations

24 comprise: i) thick-bedded structureless or planar laminated sandstones that pinch and swell, and are

25 associated with underlying debrites; ii) argillaceous and mudclast-rich hybrid beds; and iii) current

26 ripple-laminated sandstones and siltstones. Typically, frontal fringes contain high proportions of

27 hybrid beds and transition from thick-bedded sandstones over length-scales of 1 to 2 km. In

28 contrast, lateral fringe deposits tend to comprise current ripple-laminated sandstones that transition

29 to thick-bedded sandstones in the lobe axis over several kilometers. Variability of primary flow

30 processes are interpreted to control the documented differences in facies association. Preferential

31 deposition of hybrid beds in frontal fringe positions is related to the dominantly downstream

32 momentum of the high-density core of the flow. In contrast, the ripple-laminated thin beds in lateral

33 fringe positions are interpreted to be deposited by more dilute low-density (parts of the) flows. The

34 development of recognition criteria to distinguish between frontal and lateral lobe fringe

35 successions is critical to improving paleogeographic reconstructions of submarine fans at outcrop

36 and in the subsurface, and will help to reduce uncertainty during hydrocarbon field appraisal and

37 development.

38

39   **INTRODUCTION**

40 Traditionally, submarine lobe deposits are described as simple radial bodies that thin and fine from

41 an apex (e.g. Mutti, 1977; Normark, 1978; Lowe, 1982; Bouma, 2000). However, it has been

42 recognized from outcrop and geophysical studies that the anatomy of lobe deposits can be more

43 complicated in terms of facies distribution and geometry (e.g. Nelson et al., 1992; Twichell et al.,

44 1992; Bouma and Rozman, 2000; Gervais, 2006; Hodgson et al., 2006; Deptuck et al., 2008; Prélat et

45 al., 2009; Groenenberg et al., 2010; Etienne et al., 2012). Prélat et al. (2009) proposed four sub-

46 environments for lobe deposits that are characterized by specific facies associations and thickness

47 trends, termed lobe axis, lobe off-axis, lobe fringe and lobe distal fringe (Fig. 1a).

48   Placing constraints on the temporal and spatial variability of lobe fringe successions is important to

49   help improve reconstructions of deep-water fans, and to provide suitable building blocks for

50   reservoir modelling and to reduce uncertainty in the evaluation of subsurface stratigraphic traps

51   (e.g. Biddle and Wiechowsky, 1994; Etienne et al., 2012; Bakke et al., 2013; Collins et al., 2015;

52   Grecula et al., 2015). Hybrid beds (e.g. Haughton et al., 2003; Talling et al., 2004; Haughton et al.,

53   2009; Davis et al., 2009) and heterolithic deposits dominated by thin-bedded turbidites, have been

54   associated with lobe fringe environments (Ito, 2008; Hodgson, 2009; Talling et al., 2012a; Etienne et

55   al., 2012; Grundvåg et al., 2014; Patacci et al., 2014; Collins et al., 2015; Fonnesu et al., 2015, Porten

56   et al., 2016; Southern et al., 2016). Previous work on lobe fringe successions has focused on pinch-

57   out geometries (e.g. Rozman, 2000; Marini et al., 2011; Etienne et al., 2012; Nagatomo and Archer,

58   2015). Some authors (e.g. MacPherson, 1978; Pickering, 1981, 1983) have documented differences

59   between down-dip and across-strike facies transitions in lobe deposits. However, detailed

60   depositional architecture, recognition criteria and facies variability between down-dip (frontal) and

61   across-strike (lateral) lobe fringe environments remain poorly constrained.

62   The aim of this integrated outcrop and core study is to assess the difference between frontal and

63   lateral lobe fringe successions using the paleogeographically well-constrained Fan 4 succession of

64   the Skoorsteenberg Formation, Karoo Basin, South Africa. Specific research objectives are as follows:

65   1) to establish the characteristic facies associations that distinguish the different lobe fringe settings;

66   2) to interpret flow processes that produce the observed facies variability; 3) to discuss the role of

67   confinement in the distribution and character of lobe fringes; and 4) to assess the implication of the

68   results for subsurface applications.

69   **GEOLOGICAL SETTING**

70   The Karoo Basin has been interpreted as a retroarc foreland basin connected to a magmatic arc and

71   fold-thrust belt (Cape Fold Belt) (Visser & Prackelt, 1996; Visser, 1997; Catuneanu et al., 1998).

72   Alternatively, Tankard et al. (2009) argue that subsidence during the early, deep-water, phase of

73   deposition, which is the focus of this study, pre-dates the effects of loading by the Cape Fold Belt,

74   and was induced by dynamic topography associated with mantle flow processes coupled to distant

75   subduction of the paleo-Pacific plate (Pysklywec & Mitrovica, 1999). The basin-fill comprises the

76   Karoo Supergroup and records sedimentation from Late Carboniferous to Early Jurassic. The Karoo

77   Supergroup comprises the glacial Dwyka Group, the deep- to shallow-marine Ecca Group and the

78   non-marine (fluvial) Beaufort Group. The Ecca Group, which is the focus of this study, represents a

79   shallowing-upward succession of sediments from deep-water to fluvial settings (Flint et al., 2011).

80   The Tanqua depocentre is located in the southwest of the Karoo Basin adjacent to the Cederberg

81   branch of the Cape Fold Belt (Fig. 2a). Here, the Lower Ecca Group comprises the Prince Albert

82   Formation (shallow-marine), the Whitehill Formation (deep-marine) and the Collingham Formation

83   (deep-marine); the Upper Ecca Group comprises the Tierberg Formation (basin-plain), the

84   Skoorsteenberg Formation (basin-floor to base-of-slope), the Kookfontein Formation (slope to shelf-

85   edge) and the Waterford Formation (shoreface) (Fig. 2b; Bouma & Wickens, 1991; Wickens, 1994).

86   The Skoorsteenberg Formation (250 m thick; Bouma & Wickens, 1994) is subdivided into five sand-

87   prone bodies. The lower four sandstone bodies (Fans 1-4) have been interpreted as basin-floor fans

88   (Morris et al., 2000; Wickens & Bouma, 2000, Johnson et al.,2001), whereas the fifth (Unit 5) has

89   been interpreted as a lower slope to base-of-slope system (Wickens & Bouma, 2000; Wild et al.,

90   2005 Hodgson et al., 2006). Although a submarine fan represents a system built up by channels and

91   lobes, the term 'Fan' is retained here as a lithostratigraphic descriptor for consistency with previous

92   literature. Fans 1-4 are each up to 65 m thick, with gradational to sharp bases and tops (Johnson et

93   al., 2001) separated by claystones and siltstones (Van der Werff & Johnson, 2003a). Each fan is

94   interpreted as a lowstand systems tract, with the overlying fine grained deposits of regional extent

95   representing the related transgressive and highstand systems tracts (Goldhammer et al., 2000;

96   Johnson et al., 2001; Hodgson et al., 2006; Hodgson, 2009).

97   This study focuses on the lobe deposits of Fan 4, a lobe complex-set (Fig. 1b), in an 800 km^2 study

98   area (Fig. 2a). Fan 4 is up to 65 m thick (Johnson et al., 2001) and is characterized by a high degree of

99   amalgamation in the Skoorsteenberg area (Fig. 3; Dudley et al., 2000). Paleocurrents and thickness

100   distributions indicate that sediment was sourced from both the southwest and west (Dudley et al.,

101   2000; Hodgson et al., 2006), in contrast to the underlying fans (Fans 1-3) that are point sourced from

102   the SW. General paleocurrent orientations are to the east and northeast (Wickens & Bouma, 2000;

103   Hodgson et al., 2006). Fan 4 is divided into two sand-rich units named the lower and upper

104   sandstone divisions (Wickens & Bouma, 2000; Hodgson et al., 2006) separated by a thin-bedded

105   siltstone package that is up to 6 m thick in the south and thins and fines northward. The upper

106   division thickens to the north where the lower division thins, which was suggested by Hodgson et al.

107   (2006) to indicate compensational stacking. The stratigraphy of Fan 4 has been revised to show that

108   the lower sandstone division comprises one sand-prone lobe complex, whereas the upper division

109   comprises two sand-prone lobe complexes, separated by thin-bedded heterolithic lobe complex

110   fringe strata.

111

112   **METHODOLOGY**

113   For this study, 24 sections were measured in strategically chosen locations (Fig. 3) in order to collect

114   a data set that provides 3-D constraints. Graphic sedimentary logs record lithology, paleocurrent and

115   bed thickness data. Detailed bed-by-bed sections (see section locations on Fig. 3; ranging from 3 to

116   60 m in length and totaling 510 m in cumulative thickness) record grain size, sedimentary structures

117   and bounding surfaces of beds. Logs were recorded at 1:25 scale in the field. Four newly drilled,

118   near-outcrop cores (see well locations on Fig. 3) intersect Fan 4 (212 m total thickness) and were

119   logged at 1:4 scale. These data were augmented with three core logs (see locations of NOMAD –

120   Novel Modelled Architecture of Deepwater reservoirs – project; wells on Figure 3; 128 m cumulative

121   thickness) and 19 graphic logs collected during previous research (Hodgson et al., 2006; Prélat et al.,

122   2009) (Fig. 3). Outcrop sections and core logs were redrawn at 1:50 scale for correlation purposes.

123   The base of the mudstone and siltstone interval that separates the lower and upper sandstone

124   division of Fan 4 was used as a correlation datum. Paleocurrent measurements (108 in total) were

125   collected from current-ripple and climbing-ripple laminated sandstones, and flutes and grooves

126   preserved as casts on bed bases. To determine facies associations and architectures of frontal and

127   lateral fringe deposits at the scale of individual lobes, the hierarchy and paleogeography of Fan 4

128   was revised to improve the spatial understanding of lobe distribution.

129

130   **MODEL OF LOBE ANATOMY**

131   *Hierarchy*

132   A five-fold hierarchy of lobes in the Tanqua was proposed by Prélat et al. (2009): 1) a 'bed'

133   represents a single depositional event; 2) one or more beds form a 'lobe element'; 3) several lobe

134   elements that are divided by thin siltstone intervals stack to form a 'lobe'; 4) one or more lobes stack

135   to form a 'lobe complex' (Fig. 1b). The hierarchy can be extended to the 'lobe complex set', which is

136   formed by the stacking of one of more related lobe complexes within the same lowstand systems

137   tract (Fig 1b). Prélat and Hodgson (2013) demonstrated that extensive meter-thick, thin-bedded

138   units between sand-rich lobes, originally referred to as 'interlobes' by Prélat et al. (2009), represent

139   the distal fringes of lobes. Typically, these are separated from sand-rich lobe deposits (axis and off-

140   axis) across an abrupt surface interpreted to mark an up-dip channel avulsion (Prélat and Hodgson,

141   2013). Thicker and more extensive thin-bedded successions can be interpreted as the fringes of lobe

142   complexes (Prélat and Hodgson, 2013).

143   *Sedimentary facies and facies associations*

144   Aspects of the sedimentary facies and related environments of deposition of the Skoorsteenberg

145   Formation have been described in detail previously (e.g. Morris et al., 2000; Johnson et al., 2001; van

146   der Werff and Johnson 2003; Hodgson et al., 2006; Luthi et al., 2006; Prélat et al., 2009; Hodgson,

147   2009, Jobe et al., 2012; Hofstra et al., 2015). Individual facies encountered in both outcrop (Fig. 4a-f)

148   and core (Fig. 5a-f) datasets are summarized in Table 1. The facies combine into common facies

149   associations representing different lobe environments: lobe axis, lobe off-axis, lobe fringe and lobe

150   distal fringe (Prélat et al., 2009; Fig. 1a). The boundaries between these environments are

151   transitional. This fourfold division has been applied to several outcrop studies (e.g. Etienne et al.,

152   2012; Prélat and Hodgson, 2013; Grundvåg et al., 2014; Spychala et al., 2015; Marchand et al., 2015;

153   Masalimova et al., 2016). Lobe dimensions from several studies of sand-rich systems (Jegou et al.,

154   2008; Saller et al., 2008; Deptuck et al., 2008; Prélat et al., 2009; Sømme et al., 2009) show that

155   these bodies have elongate shapes with length-to-width ratios of 1.7 – 3.6 (Prélat et al., 2010).

156   Average dimensions of lobes in the Tanqua depocentre are 27 km (length) × 13 km (width) × 5 m

157   (thickness) (Fan 3, Prélat et al., 2009). Similar dimensions are expected for the lobes of Fan 4 as it

158   was deposited under similar conditions (e.g. relatively unconfined, similar grain-size range), and

159   similar lobe dimensions are identified across different unconfined systems (Prélat et al., 2010).

160   **Lobe axis**.---Lobe axis deposits are dominated by thick-bedded, structureless sandstone (F1; Figs. 4a,

161   5a; Table 1) with subordinate planar laminated (F2; Figs. 4b, 5b; Table 1) and banded sandstone (F3;

162   Fig. 5c; Table 1) in minor proportions. The lobe axis setting is characterized as 85–100% sandstone.

163   Multiple zones of amalgamation occur across strike (Prélat et al., 2009) and can form packages up to

164   5 m thick where there is scouring at the base of the lobe. The deposits of the lobe axis are laterally

165   extensive down-dip and across strike for several hundred meters, and generally show tabular

166   geometries (Fig. 4a). Units of high amalgamation can be traced into well-bedded units of the lobe

167   off-axis towards the frontal and lateral margin of the lobe deposits.

168   **Lobe off-axis**.---Lobe off-axis deposits comprise well stratified medium-bedded structured sandstone

169   (F2; Table 1) and are typically 2 to 4 m thick. Lobe off-axis deposits are characterized by 50–85%

170   sandstone. They show tabular geometries in outcrop and can be traced out for several hundred

171   meters in both dip and strike directions.

172   **Lobe fringe**.---Lobe fringe deposits comprise a range of facies, including structureless sandstone (F1),

173   hybrid beds (F4; Figs. 4c,d; Table 1), debrites (F5; Fig. 5e; Table 1) and heterolithic packages (F6; Figs.

174   4d, 5e; Table 1). Lobe fringe deposits are characterized by 20–50% sandstone. Typical thicknesses

175   range between 0.1 and 2 m. Several meter-thick successions (>2 m) are interpreted as fringes to lobe

176   complexes; such accumulations can be walked out into thick lobate sandstone units without

177   truncation (cf. Prélat and Hodgson, 2013). At outcrop, lobe fringe deposits can show either tapering

178   or pinch-and-swell geometries. The pronounced pinch-and-swell geometries form lenticular bodies,

179   even though no evidence of truncation is observed (Bouma and Rozman, 2000; Groenenberg et al.,

180   2010). The lateral extent of lobe fringe deposits is variable and ranges from a few to several

181   kilometers. The transition from lobe fringe to lobe distal fringe environment marks the sand pinch-

182   out of the system.

183   **Lobe distal fringe**.---The lobe distal fringe environment is dominated by thin-bedded siltstone

184   deposits (F7; Figs. 4e; 5g; Table 1). Some thin very fine-grained sandstone beds are intercalated in

185   these siltstone-prone packages (<20% sandstone). Siltstones can aggrade to form bedded

186   successions of several meters in thickness. Lobe distal fringe deposits form an extensive 'halo'

187   around the main sand-prone lobe body and extend for several kilometers. Their dimensions have not

188   been established.

189   In summary, lobe axis and off-axis deposits build the core of a lobe body and are dominated by

190   structureless and structured sandstone. Sandstone percentage decreases towards the lobe fringe

191   and is lowest in distal lobe fringe environments.

192

193   **ARCHITECTURE**

194   *Thickness distribution and paleoflow directions*

195   Fan 4 is subdivided into a lower and upper sand-prone division, separated by a thin-bedded

196   heterolithic division (Fig. 6, 7a). The two sand-prone divisions of Fan 4 show different thickness

197   trends and paleocurrent patterns.

198   The lower, sand-prone division has a maximum thickness of ~25 m in the southern part of the study

199   area (Fig. 6). Thinning is documented to the north and the northeast. The lower division records

200   paleoflow to the northeast but this trend is more northwards in the northern part of the study area

201   (Fig. 6). Correlation panels (Fig. 7) show that down-dip pinch-out of lobe deposits occurs in several

202   areas, such as around BK, NB2, GBE, OC7 and Ios6 area (Fig. 7). The final sand-pinch out to the

203   northeast occurs in the Vaalfontein- Sout Rivier area (Fig. 3). Notable lateral thinning across strike

204   towards the east (NS3) can be observed (~5.5 m/km). Thin (< 2 m thick) siltstone deposits are

205   deposited farther to the north where they thin gradually.

206   The thin-bedded heterolithic division that separates the lower and upper sand-prone divisions of Fan

207   4 thins and fines over 30 km from Bizansgat in the S (~6 m) gradually to Sout Rivier in the N (~0.7 m)

208   (Fig. 8).

209   The upper sand-prone division of Fan 4 has more complicated facies, thickness and paleoflow

210   distributions. There are two areas that show high thickness values (Fig. 6). Maximum thickness in the

211   southern study area is ~35 m (Bizansgat) from where the division thins to the north and northeast,

212   with paleoflow trends that conform to the northeasterly to northerly trends of the lower division

213   and of underlying Fan 3 (cf. Wickens and Bouma, 2000; Hodgson et al., 2006; Prélat et al., 2009). In

214   the area around Skoorsteenberg, the upper division is 47 m thick (Fig. 6) with paleoflow trends that

215   record a radial spread of directions from the northeast to southeast (Fig. 6; cf. Hodgson et al., 2006).

                                            9

216   A laterally extensive ~3 m thick extensive thin-bedded unit is present towards the top of the upper

217   division. Thinning also occurs to the northeast and southeast, with the rate of thinning to the

218   northeast being highest (~6.9 m/km). The most northeastern outcrops around Katjiesberg (down-

219   dip) record dominantly northward paleocurrents and are characterized by highly variable

220   thicknesses, which range between 2 and 14 m and reflect a pinching and swelling trend of the

221   deposits (Fig. 6b). Correlation panels (Fig. 7) show that the oldest deposits pinch-out in the Sout

222   Rivier area, and the youngest deposits do not reach as far as the Katjiesberg area; therefore, an

223   overall basinward to landward stacking pattern is constrained.

224

225   *Hierarchy of Fan 4*

226   Thicknesses, facies associations and paleocurrents indicate that the lower division of Fan 4

227   comprises one lobe complex (Fig. 8a, LC1) that was fed by flows from the southwest. The heterolithic

228   succession that separates the lower and upper sand-prone divisions of Fan 4 comprises thin-bedded

229   silty mudstone, siltstone and sandstones (heterolithic deposits) (Fig. 8b, c). The facies association,

230   the lack of hemipelagic claystone, and the thickness patterns, collectively suggest this succession

231   most-likely represents the distal fringe of a lobe complex (cf. Prélat et al., 2009). The associated

232   sand-prone deposits of this lobe complex (LC2) are inferred to have been located to the west,

233   beyond the outcrop exposure. Paleoflow and thickness trends suggest two distinct sediment entry

234   points for the upper sand-prone division of Fan 4 (Wickens & Bouma, 2000; Dudley et al., 2000;

235   Hodgson et al., 2006). The upper part of Fan 4 comprises two sand-prone lobe complexes (LC3 and

236   LC5). They both have maximum thicknesses in the Skoorsteenberg area, and are separated by a ~3 m

237   thick extensive thin-bedded unit that is interpreted as the fringe of another lobe complex (LC4; Fig.

238   8a).

239   *Facies distribution*

240 Successive lobe deposits in weakly confined settings build lobe complexes that commonly exhibit

241 compensational stacking patterns driven by avulsion of distributive channels (Pickering, 1981;

242 Deptuck et al., 2008; Prélat et al., 2009; Prélat and Hodgson, 2013) (Fig. 9a-d). The distribution of

243 sedimentary facies are described from LC1 (lower division; Fig. 10) and LC 3-5 (upper division; Fig.

244 10b).

245 In the southern part of the study area, where LC1 is thickest, the deposits are dominated by

246 structureless (F1) and structured sandstone (F2; see Table 1; F1+F2> 75%) (Fig. 10). The proportion

247 of hybrid beds (F4) increases northwards where they can represent up to 50% of the thickness (e.g.

248 Vaalfontein; Fig. 3). Heterolithic deposits (F6) dominate the basal part of LC1 around the NB2, NS2

249 and NS1 well locations (Fig. 3). The NS3 well is represented by heterolithic deposits (~70%), siltstone

250 (~10%) and mudstone (~20%) (Fig. 11). Structureless sandstones are present in the northern part of

251 the study area in highly variable proportions (15% to 50% of deposits) (Fig. 10a). Sandstone-pinch-

252 out of the lobe complex occurs in the Sout Rivier area (Fig. 7). Northwards, the deposits of LC1

253 consist entirely of thin-bedded siltstones.

254 The upper part of Fan 4, which comprises LC3, LC4, and LC5, is characterized by a higher proportion

255 of structureless sandstone. The southern study area is marked by structureless (F1), structured (F2)

256 and banded sandstones (F3), which represent the bulk of deposits (50% to 75%). Hybrid beds (F4)

257 contribute 20% of the facies composition in Koppieskraal; elsewhere they contribute less than 10%.

258 Heterolithic deposits (F6) contribute 15% to 35% towards the central study area but less than 10% in

259 the southern study area. The northern study area is dominated by structureless sandstone deposits

260 (more than 50%) with the highest proportion observed in the Skoorsteenberg area (up to 80%).

261 Structured sandstone is a minor contributor (~ 15%). Hybrid beds represent less than 10% of

262 deposits, and heterolithic deposits commonly represent 10% to 15%. In the Katjiesberg area in the

263 northeast, almost no heterolithic deposits are present (<2%) but thin-siltstone deposits are

264 intercalated with structureless sandstone and hybrid beds.

265

266   *Fan 4 paleogeographic reconstruction*

267   Integration of paleoflow and thickness trends with facies distribution enables reconstruction of the

268   lower (LC1) and upper (LC3-5) divisions of the Fan 4 lobe complex set (Fig. 10). Paleoflow directions

269   for LC1 are both to the north and northeast (Fig. 6), whereas sediment entered from the southwest

270   (e.g. Dudley et al., 2000; Hodgson et al., 2006). This suggests that the northward pinch-out

271   represents a frontal fringe and the eastern termination a lateral pinch-out at the scale of the lobe

272   complex (Fig. 7). Younger lobe deposits of LC1 pinch-out successively farther to the north, which is

273   consistent with a progradational stacking pattern (*sensu* Hodgson et al., 2016), and frontal pinch-out

274   at the scale of a lobe. The frontal sand pinch-out of LC1 in the Sout Rivier area (Fig. 2) is associated

275   with a pinch-and-swell geometry of lobes and predominantly structureless sandstone and hybrid

276   beds (Fig. 7). A 'halo' of thin-bedded siltstone, which represents distal lobe fringe deposits, is

277   deposited farther to the north. Deposits across strike (lateral) to the east are dominated by

278   heterolithic deposits (NS3; Figs. 10, 11). The change in facies is associated with thinning of LC1.

279   Therefore, the deposits observed in NS3 represent several lateral lobe fringes that stack to form the

280   lobe complex fringe. Similar facies changes have also been identified on the western margin of LC1

281   by Hodgson et al. (2006) in the Los Kop area (marked in Fig. 10).

282   The upper division of Fan 4 comprises two sand-rich lobe complexes, LC 3 and LC5, separated by an

283   extensive thin-bedded heterolithic interval interpreted as the lobe complex fringe, LC 4. LC3 has two

284   thick and axial zones, in the Bizansgat and in the Skoorsteensberg area (Fig. 9). The facies

285   distribution patterns and paleoflow (Fig. 6) indicate that deposition could have been by two coeval

286   systems with different entry points. This interpretation is supported by the lack of clear trends in

287   facies distributions over the study area pointing to a complicated interaction of depositional systems

288   in the south and north. The deposits are treated as a single lobe complex because no bounding

289   surface or extensive thin-bedded units separating the two thick and axial areas have been observed

290   that could have been the result of avulsion. Generally, facies distributions suggest that, in the

291   southern part of LC3, there was compensational stacking of lobes as heterolithic intervals with

292   hybrid beds alternate with packages of structured and structureless sandstones across abrupt

293   surfaces in vertical sections. The northern part of LC3 and LC5 show dominantly aggradational

294   stacking patterns of lobes (Fig. 9). Facies changes (e.g. F1 and F3) can be explained by

295   compensational stacking on lobe element-scale (Prélat et al., 2009; Etienne et al., 2012; Prélat &

296   Hodgson, 2013) and scouring and amalgamation of lobe axes. Abrupt facies changes from

297   heterolithic deposits (distal lobe fringes) to sand-prone lobes suggest sufficient space for lateral

298   compensation. In the down-dip direction (Katjiesberg) of LC3, structureless sandstone, siltstone and

299   hybrid beds that show pinch-and-swell geometries dominate the lobe complex (Fig. 13, 14). These

300   are interpreted as stacked frontal lobe fringe deposits. The low proportion of hybrid beds otherwise

301   in the northern part of LC3 reflects the complicated 3D geometry of individual lobes. Integration of

302   paleocurrents and isopach maps would predict that a higher proportion of hybrid beds may be found

303   in the subcrop to the east. Due to the complexities in LC3 and the fragmented outcrop record of LC5,

304   the architecture of lobes, from their axes to their fringes has focused on LC1. The results can be

305   applied to the younger lobe complexes where data constraints permit.

306

307   **LOBE FRINGE ASSOCIATIONS**

308   Paleogeographic reconstruction of the Fan 4 lobe complex 1 (LC1) shows that lateral and frontal lobe

309   fringe environments can be well constrained in a lobe complex using isopach maps and

310   paleocurrents (Fig. 10). Integration of these data with mapped sand pinch-outs enables the relative

311   position and orientation of individual lobe bodies to be determined with confidence (Fig. 10).

312   Generally, their dip direction is to the N, whereas their strike direction is to the E and W. Figure 12

313   depicts characteristic transitions in facies at lateral (Fig. 12a) and frontal (Fig. 12b) lobe fringes in

314   LC1, which are described in detail below. Frontal and lateral lobe fringe environments are shown to

315   display characteristic facies associations and geometries that are summarized in Table 2.

316

317   *Lateral lobe fringe*

318   Figure 12a shows a correlation panel of a single lobe from Hammerkranz to NS2 in LC1 (Figs. 3 and

319   10a). The lobe is defined by sharp lower and upper changes in facies to distal lobe fringe successions.

320   Using the well-constrained paleogeographic map of LC1, this is a lateral transition from axial lobe

321   deposits (dominated by F1 and F2) to a succession that is dominated by structured sandstone and

322   heterolithic deposits. The lobe thins from 5.5 m in the axial position to 1.9 m in the lateral position in

323   4 km (0.9m/km rate of thinning). The lower part of the lobe exhibits a transition into thin-bedded

324   lobe fringe deposits, and the upper part of the lobe exhibits a transition to traction dominated

325   sandstones. Bed amalgamation is not observed.

326   The NS3 core (Fig. 11) shows an example of the lateral margin of a lobe complex (LC1) where all

327   lobes pass stratigraphically into an aggradational stack of fringe deposits. The integration of

328   observations of the detailed facies transition and the lobe fringe-dominated succession in NS3 allows

329   the following characteristics for lateral lobe fringes to be established. The lateral lobe facies

330   association is dominated by thin-bedded (>0.2 m) heterolithic deposits of structureless or planar

331   laminated siltstone, and wavy, ripple and climbing-ripple laminated very-fine grained sandstone

332   (Figs. 14a, b, 15b; Table 2). Rare, debrites are present (Fig. 15b). Lateral lobe fringe deposits

333   experience gradual decrease in sand-content (~50% at the transition of the lobe-off axis to ~20% at

334   transition to distal lobe fringe) and bed thickness (average bed thickness of 0.6 m in lobe off axis to

335   average bed thickness of 0.1 m in lateral lobe fringe). Therefore, pinch-out occurs over several

336   kilometers through thinning and fining of the deposits. In outcrop (e.g. LC4; Fig. 14b), lateral lobe

337   fringes commonly show tabular geometries at the scale of observation (Figs. 14a, b; Table 2). A

14

338   similar facies transition to a lateral fringe in a lobe was well constrained in the underlying Fan 3 by

339   Prélat et al. (2009, their Lobe 6).

340

341   *Frontal lobe fringe*

342   Figure 12b shows a correlation panel of a single lobe from OC2 to OC5 in LC1 (Fig. 7 and 10). The

343   lobe is identified by abrupt lower and upper contacts to lobe distal fringe deposits. Using the well-

344   constrained paleogeographic map of LC1, this marks the frontal transition from axial lobe deposits

345   (dominated by F1) to a succession marked by hybrid bed deposits, structureless sandstone and

346   siltstone beds. Sandstone deposits show a high degree of amalgamation in OC2, and become

347   progressively less amalgamated down-dip, and increasingly intercalated with thin-bedded siltstone

348   units (Fig. 12b; Fig. 15a). The lobe deposits exhibit a pinch-and-swell geometry (thickening from 2.5

349   m in OC2 to 3.2 m in OC3 and then thinning to 2 m in OC5; Fig. 12b). The sand pinch-out of the lobe

350   occurs abruptly within few hundred meters.

351   Similar facies associations and geometries are observed in the frontal pinch-out of lobe deposits in

352   termination of LC3. The frontal lobe fringe facies association is characterized by dewatered,

353   structureless or planar laminated fine-grained sandstones (Figs. 14c, d, 15a) associated with hybrid

354   beds and rare thick debrites (Table 2). Commonly, the sandstone and hybrid beds of frontal lobe

355   fringes exhibit depositional pinch-and-swell geometries (Fig. 13), which are underlain by siltstones

356   but without any basal truncation. In map view, the pinch-and-swell geometries are mapped as

357   irregular, finger-like bodies aligned with paleoflow (Bouma & Rozmann, 2000; Van der Werff &

358   Johnson, 2003b; Prélat et al., 2009; Hodgson, 2009; Groenenberg et al., 2010). The dimensions of

359   these fingers are 200-300 m in strike width and 1.5 to 2.0 km in dip length. When sand pinch-out

360   occurs overlying sand-prone strata, pronounced fingers do not develop. The percentage of

361   structureless sandstone within the frontal lobe fringe remains high (10 to 50%) up to the point of

362 sandstone pinch-out. Commonly, sandstone pinch-out is abrupt, but thin-bedded siltstones typically

363 continue for several kilometers farther.

364

365   **DISCUSSION**

366 Lobes do not show simple thinning and fining trends in all directions away from their apex (cf.

367 Groenenberg et al., 2010). Despite showing the widest range of facies, lobe fringes are the least well

368 studied sub-environments of lobes. Lobe fringe complexity has been highlighted by MacPherson

369 (1978) and Pickering (1981; 1983), who demonstrated the significant variability of lobe (or fan)

370 fringe facies. The process reasons behind the observed differences in lateral and frontal lobes

371 fringes, and the subsurface implications of improved identification of fringe setting, are discussed

372 below.

373   *Controls on lobe pinch-out geometries*

374 Generally, lateral lobe fringe successions are predominantly characterized by deposits from low-

375 density turbidity currents, whereas frontal lobe fringes are dominated by deposits from high-density

376 turbidity currents and other high-concentration flows (structureless sandstones, debrites and hybrid

377 beds; Talling et al., 2012). Lateral lobe fringes fine and thin as they taper away from lobe axis

378 environments (Figs. 12a, 15b). In contrast, basal lobes in the frontal fringes of lobe complexes show

379 abrupt thickness and facies changes (Figs. 12b, 13, 15a). Controls on this distinctive geometry in

380 frontal lobe position could reflect either 1) influence of underlying seabed topography or 2) flow

381 processes and interactions with substrate. Finger-like pinch-outs of frontal lobes are observed within

382 successive lobes of multiple different lobe complexes within the Tanqua depocentre (Bouma &

383 Rozman, 2000; Rozman, 2000; Prélat et al., 2009; Groenenberg et al., 2010). Similar terminations

384 have been observed within other basin-floor lobe systems (Nelson et al., 1992; Twichell et al., 1992),

385 albeit occasionally misinterpreted as channel-forms (e.g. Van der Werff & Johnson, 2003b) due to

their elongated shape in planform view and their convex-up form in outcrop. Groenenberg et al. (2010) did not support the presence of pre-existing seabed topography as the main influencing factor because of the common occurrence of finger-like bodies in several basal lobes over several lobe complexes. The repeated formation of seabed relief in a radial finger-like pattern prior to initiation of each lobe complexes, was viewed as unlikely (Groenenberg et al., 2010).

Hybrid beds have been reported to be associated with distal lobe settings (Haughton et al., 2003; Talling et al., 2004; Ito, 2008; Hodgson, 2009; Kane and Pontén, 2012; Talling et al., 2012a; Grundvåg et al., 2014; Patacci et al., 2014; Collins et al., 2015; Fonnesu et al., 2015; Southern et al., 2016) and the cohesive nature of the depositing flows is suggested to control the abrupt pinch-out of deposits in this setting (Groenenberg et al., 2010; Kane et al., in review). In frontal lobe fringes, there is evidence that relatively distal turbidity currents eroded and entrained substrate material, preserved as mud-clasts and dispersed mud (Hodgson, 2009, Kane et al., in review). The combined effects of flow deceleration, and increased flow concentration through entrainment, led to enhanced flow stratification and the development of a dense, cohesive basal layer (e.g., McCave and Jones, 1988; Kane & Pontén, 2012; Talling, 2013; Kane et al., in review). The development of a dense basal layer in the flow may have suppressed upward transfer of turbulence resulting in the collapse of the upper part of the flow (McCave & Jones, 1988; Kane et al., in review). The collapse of the upper part of the flow may account for the abrupt pinch-out of both the lower and upper parts of hybrid beds in distal settings, i.e., debritic divisions of hybrid beds rarely out-run the lower cleaner sandstone division. The principal alternative, that turbidity currents fractionated their suspended load and split into forerunning turbidity currents with trailing debris flows (depositing turbidites with linked debrites, Haughton et al., 2003; Haughton et al., 2009), may account for thicker debrites, that are observed to be deposited within the finger-like structures (see Fig. 13c). These may have over-run, or taken a different course, to their forerunning turbidity currents. Deposits of high-density turbidity currents are able to create their own pathways and become successively more elongated down-dip, forming finger-like bodies. These finger-like structures of frontal lobes are connected by

412   thin-beds creating a webbed bird's foot geometry in planform (Fig. 13, 16a). This accords with results

413   by Groenenberg et al. (2010) from process-based numerical modelling of lobes, who suggested that

414   depositional relief of preceding lobes could help to focus these types of flow into distal areas.

415   Elongated beds have been produced experimentally by Luthi (1981) showing that velocity of the

416   turbidity currents was highest along the central axis. The frontal pinch-out of lobe complexes is

417   accompanied by abrupt thickness decrease and occurs over a few hundred meters (Fig. 15a).

418   The lateral fringe of a lobe forms a wedge-like geometry that thins away from the lobe axis and off-

419   axis (Fig. 15b) as deposits fine gradually over a few kilometers (Fig. 16a). Lateral lobe fringe deposits

420   dominantly record the accumulated products of low-density turbidity currents. Luthi's (1981)

421   experiments show that flow velocities are lowest in these flow marginal areas, and the flow

422   thickness decrease is greatest laterally away from the central flow axis. Depositional relief of

423   preceding lobe deposits probably had a relatively minor influence on low-density flows, as these can

424   surmount seabed topography (e.g., Brunt et al., 2004; Bakke et al., 2013). Their run-out distance is

425   therefore primarily dependent on their thickness and volume (Wynn et al., 2002). The deposits of

426   the low-density turbidity currents probably form laterally extensive radial deposits which are higher

427   in proportion at the lateral fringe, owing to the forward momentum and lack of lateral spreading of

428   the higher concentration flows in the axial areas. In the frontal fringe setting, the low-density

429   turbidity currents, for the most-part, out ran the flows responsible for depositing the hybrid beds to

430   deposit in distal fringe settings. Thin stand-alone debrites recorded in the lateral fringes deposits are

431   inferred to have been deposited by debris flows which bypassed the majority of the lobe to be

432   deposited in its fringe (Talling et al., 2012b; Ducassou et al., 2013).

433

434   *Role of confinement*

435 The difference in lateral and frontal lobe fringe within LC1 and LC3 has been documented in a

436 relatively unconfined basin-floor setting. In basins where lobes do not feel basin confinement,

437 compensational stacking will result in alternating successions of lobe axis and off-axis environments,

438 with lobe fringe and distal fringe environments (Prélat and Hodgson 2013). Therefore, it is possible

439 that frontal and lateral lobe fringes will be present in a 1-D section (e.g. core) through a single lobe

440 complex. Flow confinement has been documented to be an important autogenic factor in the

441 control of dispersal patterns and lobe stacking patterns (e.g. Piper & Normark, 1983; Smith &

442 Joseph, 2004; Amy et al., 2004, Twichell et al., 2005; Macdonald et al., 2011; Marini et al., 2011;

443 Southern et al., 2015; Marini et al., 2015).

444 With increased seabed confinement, lobes will be forced stack aggradationally or longitudinally

445 rather than compensationally. This would lead to a clearer segregation of frontal and lateral lobe

446 fringes. Even subtle intrabasinal slopes, with angles as small as a fraction of a degree, have been

447 shown to modify stacking patterns and facies distribution considerably. Spychala et al. (2016) show

448 that an intrabasinal slope (< 0.5°) in the Laingsburg depocentre, Karoo Basin, led to aggradational

449 stacking of lateral lobe fringes in multiple stacked lateral lobe complex fringes, compared to

450 compensational stacking patterns in the unconfined part of the basin. The aggradation of multiple

451 lateral lobe fringes in LC1 (Fig. 11), allied to the persistent thinning and paleocurrent trends (Fig. 10)

452 could be used to infer the presence of a subtle confining N-S oriented slope. The lateral lobe fringe

453 facies association reflects the overall aggradational trend with sedimentary features such as climbing

454 bedforms and predominant climbing-ripple lamination. Similar observations have been made from

455 the Silurian sand-prone deep-water systems of the Welsh Basin (cf. Smith 1987a,b; Wilson et al.,

456 1992; Smith 2004). It is not clear if there are distinctive lateral or frontal facies trends in more highly

457 confined basin settings; this is an area that warrants further investigation.

458 *Subsurface implications*

459   The documented differences in sedimentology and architecture of lateral and frontal lobe fringes

460   have several implications for subsurface applications. Facies recognition criteria established in this

461   study can help determine internal division of lobe complexes in 1D datasets, e.g. core data, to help

462   improve paleogeographic reconstructions. Stacking of lobe fringe types could be used as an indicator

463   of the degree and orientation of seabed topography. In an unconfined setting, vertical stacking of

464   frontal and lateral lobe fringes in a lobe complex are possible, whereas in settings influenced by

465   relief stacked successions of frontal lobe fringes (hybrid bed-rich deposits) or lateral lobe fringes

466   (thin-bedded heterolithic deposits) in a lobe complex can accumulate.

467   Lobe fringe deposits form heterogeneities within deep-water fan deposits (e.g. Etienne et al., 2012;

468   Collins et al., 2015; Grecula et al., 2015). Generally, frontal lobe fringes have higher sandstone

469   percentages (~50%). However, the high proportion of hybrid beds means that permeability values

470   are likely to be considerably lower than within structureless and structured sandstones. This

471   conforms to the conclusions of Marchand et al. (2015) who observed that the presence of silt-sized

472   particles and ductile, platy shaped grains in distal sand-rich successions decreases reservoir quality;

473   furthermore, Porten et al. (2016) demonstrate that for a given porosity, hybrid beds may have

474   permeabilities one or two order of magnitude lower than turbidites. Thick-bedded deposits can be

475   expected in frontal lobe fringes, but amalgamation is rare. Lateral fringe deposits gradually decrease

476   in sand-content (~50% at transition structured sandstones of the lobe-off axis to ~20% at transition

477   to distal lobe fringe) and bed thickness. Bed amalgamation is not observed. Permeability and

478   porosity values are expected to be relatively low, and decrease gradually as the deposits thin and

479   fine. Lobe fringes have the potential to be stratigraphic traps (*sensu* Levorsen, 1936) with their

480   confining element being lateral depositional changes especially at the margins of a lobe complex

481   that are encased by hemipelagic deposits. Lateral lobe fringes are dominated by lateral gradation of

482   sandstone to silty mudstone with widespread waste zones (cf. Rittenhouse, 1972; Biddle and

483   Wielchowsky, 1994). Frontal lobe fringes, however, are characterized by their abrupt pinch-out style

484   (cf. Rittenhouse, 1972; Biddle and Wielchowsky, 1994) and are connected to the high-quality

485   reservoir sandstones of the lobe axis and lobe off-axis up-dip. Therefore, frontal fringes are

486   considered to have greater potential as viable stratigraphic trap targets.

487   **CONCLUSIONS**

488   Lobe fringe successions are the least well studied sub-environments of submarine lobe deposits

489   despite showing the widest range of facies and being critical to many lobe stratigraphic trap targets.

490   An integrated outcrop and research borehole data set uses thickness and grain-size trends, facies

491   distribution and depositional geometries, to constrain two distinctive lobe fringe settings; frontal

492   lobe fringe and lateral lobe fringe. Frontal lobe fringes are characterized by structureless sandstone

493   and hybrid bed deposits. They can exhibit elongated finger-like shapes with abrupt sandstone pinch-

494   out. Lateral fringes are dominated by heterolithic traction-influenced deposits that gradually thin

495   and fine to form a simple taper. Therefore, lobes do not show simple thinning and fining trends in all

496   directions away from their apex.

497   The dominant flow processes control the differences in facies associations and geometries of the

498   two lobe fringe sub-environments. Frontal lobe fringes are characterized by deposits of the highest

499   energy parts of turbidity currents that passed through the axis of the lobe, and maintained the

500   highest momentum. In contrast, lateral fringes are dominated by deposits from low-density turbidity

501   currents that are prone to tractional reworking. Distinguishing frontal and lateral lobe fringes

502   improves prediction of facies distributions, and their stacking patterns, and can help to build more

503   accurate reconstructions of lobe complexes, even without well-exposed outcrops arranged in 3-D

504   distributions. Compensational stacking of lobes in unconfined settings can lead to stratigraphic

505   alternations of frontal and lateral lobe fringes in lobe complexes, whereas it is speculated that in

506   confined settings aggradational to longitudinal stacking of frontal and lateral fringes will result in

507   stronger stratigraphic and geographic segregation. The development of recognition criteria to

508   distinguish between frontal and lateral lobe fringes will help to support paleogeographic

509   reconstructions, and inform the appraisal of stratigraphic trap prospects in the subsurface.

21

REFERENCES

521   Allen, J.R.L., 1971, Instantaneous sediment deposition rates deduced from climbing-ripple cross-

522   lamination: Journal of Geological Society London, *v.* 127, p. 553-561.

523

524   Allen, J.R.L., 1973, A classification of climbing-ripple cross-lamination: Journal of the Geological

525   Society London, *v.* 129, p. 537–541.

526

527   Allen, J.R.L., 1982, Sedimentary Structures: Their Character and Physical Basis vol. 1,2: Elsevier,

528   Amsterdam (593pp., 663 pp.)

529

530   Amy, L.A., McCaffrey, W.D. and Kneller, B.C., 2004, The influence of a lateral basin-slope on the

531   depositional patterns of natural and experimental turbidity currents, *in* Joseph, P. and Lomas, S.A,

532   eds., Deep-Water Sedimentation in the Alpine Basin of Se France: New Perspectives on the Gres

533   d'Annot and related systems: Geological Society London Special Publication, *v.* 221, p. 311-330.

534

535   Arnott, R.W.C., and Hand, B.C., 1989, Bedforms, Primary Structures and Grain Fabric in the Presence

536   of Suspended Sediment Rain: Journal of Sedimentary Petrology, *v.* 59, p. 1062-1069.

537

538   Bakke, K., Kane, I.A., Martinsen, O.J., Petersen, S.A., Johansen, T.A., Hustoft, S., Jacobsen, F.H., and

539   Groth, A., 2013, Seismic modeling in the analysis of deep-water sandstone termination style: AAPG

540   Bulletin, *v.* 97, p. 1395- 1419.

541

542   Best, J., and Bridge, J., 1992, The morphology and dynamics of low amplitude bedwaves upon upper

543   stage plane beds and the preservation of planar laminae: Sedimentology, *v.* 39, p. 737-752.

544

545   Biddle, K.T., and Wielchowsky, C.C., 1994, Hydrocarbon traps: AAPG Memoir, *v.* 60, p. 219-235.

546

547   Bouma, A.H., 1962, Sedimentology of some flysch deposits: a graphic approach to facies

548   interpretation. Elsevier, Amsterdam/New York, 168pp.

549

550   Bouma, A.H., 2000, Fine-Grained, Mud-Rich Turbidite Systems: Model and Comparison with Coarse-

551   Grained, Sand-Rich Systems, *in* Bouma, A.H., and Stone, C.G., eds., Fine-grained Turbidite Systems ,

552   AAPG Memoir 72/SEPM Special Publication, *v.* 68, p. 9-19.

553

554   Bouma, A.H., and Wickens, H.d.V., 1991, Permian passive margin submarine fan complex, Karoo

555   Basin, South Africa: possible model to Gulf of Mexico: Gulf Coast Association of Geological Societies,

556   v. 41, p. 30-42.

557

558   Bouma, A.H., and Rozman, D.J., 2000, Characteristics of fine grained outer fan fringe turbidite

559   systems, *in* Bouma, A.H., and Stone, C.G., eds., Fine-grained Turbidite Systems, AAPG Memoir

560   72/SEPM Special Publication, *v.* 68, p. 291–298.

561

562   Brunt, R.L., McCaffrey, W.D., and Kneller, B.C., 2004, Experimental modeling of the spatial

563   distribution of grain size developed in a fill-and-spill mini-basin setting: Journal of Sedimentary

564   Research, *v.* 74, p. 438-446.

565

566   Catuneanu, O., Hancox, P.J., and Rubridge, B.S., 1998, Reciprocal flexural behaviour and contrasting

567   stratigraphies: a new basin development model for the Karoo retroarc foreland system, South Africa:

568   Basin Research, *v.* 10, p. 417-439.

569

570   Collins, J., Kenyon-Roberts, S., Cullen, B., White, J., Bordas-Le Floch, N., and Downey, J., 2015, Arran

571   Field: a complex heterolithic reservoir on the margins of the Forties Fan System, *in* McKie, T., Rose,

572   P.T.S., Hartley, A.J., Jones, D.W. and Armstrong, T.L., eds., Tertiary Deep-Marine Reservoirs of the

573   North Sea Region: Geological Society London Special Publication, *v.* 403, p. 185-217.

574

575   Davis, C., Haughton, P., McCaffrey, W., Scott, E. Hogg, N., and Kitching, D., 2009, Character and

576   distribution of hybrid sediment gravity flow deposits from the outer Forties Fan, Paleocene Central

577   North Sea, UKCS: Marine and Petroleum Geology, *v.* 26, p. 1919-1939.

578

579   Deptuck, M.E., Piper, D.J.W., Savoye, B., and Gervais, A., 2008, Dimensions and architecture of late

580   Pleistocene submarine lobes off the northern margin of East Corsica: Sedimentology, v. 55, p. 869–

581   898.

582

583   Ducassou, E., Migeon, S., Capotondi, L., and Mascle, J., 2013, Run-out distance and erosion of debris-

584   flows in the Nile deep-sea fan system: Evidence from lithofacies and micropaleontological analyses:

585   Marine and Petroleum Geology, *v.* 38, p. 102-123.

586

587   Dudley, P.R.C., Rehmer, D.E., and Bouma, A.H., 2000, Reservoir-Scale Characteristics of Fine-Grained

588   Sheet Sandstone, Tanqua Karoo Subbasin, South Africa: GCSSEPM Foundation 20th Annual Research

589   Conference. Deep-Water Reservoirs of the World, December 3-6, 200x.

590

591   Etienne, S., Mulder, T., Bez, M., Desaubliaux, G., Kwasniewski, A., Parize, O., Dujoncquoy, E., and

592   Salles, T., 2012, Multiple scale characterization of sand-rich distal lobe deposit variability: Examples

593   from the Annot Sandstones Formation, Eocene–Oligocene, SE France: Sedimentary Geology, *v.* 273-

594   274, p. 1-18.

595

596   Flint, S.S., Hodgson, D.M., Sprague, A.R., Brunt, R.L., van der Merwe, W.C., Figueiredo, J., Prélat, A.,

597   Box, D., Di Celma, C., and Kavanagh, J.P., 2011, Depositional architecture and sequence stratigraphy

598   of the Karoo basin floor to shelf edge succession, Laingsburg depocentre, South Africa: Marine and

599   Petroleum Geology, *v.* 28, p. 658-674.

600

601   Fonnesu, M., Haughton, P., Felletti, F., and McCaffrey, W., 2015, Short length-scale variability of

602   hybrid event beds and its applied significance: Marine and Petroleum Geology, *v.* 67, p. 583-603.

603

604   Gervais, A., Savoye, B., Mulder, T., and Gonthier, E., 2006, Sandy modern turbidite lobes: A new

605   insight from high resolution seismic data: Marine and Petroleum Geology, *v.* 23, p. 485-502.

606

607   Goldhammer, R.K., Wickens, D.H., Bouma, A.H., and Wach, G., 2000, Sequence Stratigraphic

608   Architecture of the Late Permian Tanqua Submarine Fan Complex, Karoo Basin, South Africa, , *in*

609   Bouma, A.H., and Stone, C.G., eds., Fine-grained Turbidite Systems , AAPG Memoir 72/SEPM Special

610   Publication, *v.* 68, p. 165-172.

611

612   Grecula, M., Hognestad, J., Price, S., Boya Ferrero, M., De Brujin, G., Noraberg, K.T., Engenes, K.,

613   Mears, P., Van Ojik, K., and McGarva, R., 2015, Interplay of fan-fringe reservoir detieriation and

614   hydrodynamic aquifer: understanding the margins of gas development in the Ormen Lange Field, *in*

615   McKie, T., Rose, P.T.S., Hartley, A.J., Jones, D.W., and Armstrong, T.L., eds., Tertiary Deep-Marine

616   Reservoirs of the North Sea Region: Geological Society London Special Publication*, v.* 403, p.157-183.

617

618   Groenenberg, R.M., Hodgson, D.M., Prélat, A., Luthi, S.M., and Flint, S.S., 2010, Flow-Deposit

619   Interaction in Submarine Lobes: Insights from Outcrop Observations and Realizations of the Process-

620   Based Numerical Model: Journal of Sedimentary Research, *v.* 80, p. 252-267.

621

622   Grundvåg, S.A., Johannessen, E.P., Helland-Hansen, W., and Plink-Björklund, P., 2014, Depositional

623   architecture and evolution of progradationally stacked lobe complexes in the Eocene Central Basin

624   of Spitsbergen: Sedimentology, *v.* 61, p. 535-569.

625

626   Haughton, P.D.W., Barker, S.P., and McCaffrey, W.D., 2003, 'Linked' debrites in sand-rich turbidite

627   systems – Origin and significance: Sedimentology, *v.* 50, p. 459-482.

628

629   Haughton, P., Davis, C., McCaffrey, W., and Barker, S., 2009, Hybrid sediment gravity flow deposits –

630   Classification, origin and significance: Marine and Petroleum Geology, *v.* 26, p. 1900-1918.

631

632   Hodgson, D.M., Flint, S.S., Hodgetts, D., Drinkwater, N.J., Johannessen, E.P., and Luthi, S., 2006,

633   Stratigraphic evolution of fine-grained submarine fan systems, Tanqua depocentre, Karoo Basin,

634   South Africa: Journal of Sedimentary Research, *v.* 76, p. 20– 40.

635

636   Hodgson, D.M., 2009, Distribution and origin of hybrids beds in sand-rich submarine fans of the

637   Tanqua depocentre, Karoo Basin, South Africa: Marine and Petroleum Geology, *v.* 26, p. 1940-1956.

638

639   Hodgson, D.M., Kane, I.A., Flint, S.S., Brunt, R.L. and Ortiz-Karpf, A., 2016, Time-Transgressive

640   Confinement On the Slope and the Progradation of Basin-Floor Fans: Implications For the Sequence

641   Stratigraphy of Deep-Water Deposits: Journal of Sedimentary Research, *v.* 86, p.73-86.

642   Hofstra, M., Hodgson, D.M., Peakall, J., and Flint, S.S., 2015, Giant-scour fills in ancient channel-lobe

643   transition zones: Formative processes and depositional architecture: Sedimentary Geology, *v.* 329, p.

644   98-114.

645

646   Hunter, R.E., 1977, Terminology of cross-stratified sedimentary layers and climbing-ripple structures:

647   Journal of Sedimentary Research, *v.* 47, p. 697–706.

648

649   Ito, M., 2008, Downfan Transformation from Turbidity currents to debris flows at a Channel-to-Lobe

650   Transitional Zone: The Lower Pleistocene Otadai Formation, Boso Peninsula, Japan: Journal of

651   Sedimentary Research, *v.* 78, p. 668-682.

652

653   Iverson, R.M., 1997, The physics of debris flow: Reviews of Geophysics, *v.* 35, p. 245-296.

654

655   Jegou, I., Savoye, B., Pirmez, C., and Droz, L., 2008, Channel-mouth lobe complex of the recent

656   Amazon fan: The missing piece: Marine Geology, *v.* 252, p. 62–77.

657

658   Jobe, Z.R., Lowe, D.R., Morris, W.R., 2012, Climbing-ripple successions in turbidite systems:

659   depositional environments, sedimentation rates and accumulation times: Sedimentology, *v.* 59, p.

660   867-898.

661

662   Johnson, S.D., Flint, S.S., Hinds, D., and Wickens, H.d.V., 2001, Anatomy of basin floor to slope

663   turbidite systems, Tanqua Karoo, South Africa: sedimentology, sequence stratigraphy and

664   implications for subsurface prediction: Sedimentology, *v.* 48, p. 987–1023.

665

666   Jopling, A.V., and Walker, R.G., 1968, Morphology and origin of ripple-drift cross-lamination, with

667   examples from the Pleistocene of Massachusetts: Journal of Sedimentary Research, *v.* 38, p. 971–

668   984.

669

670   Kane, I.A. and Pontén, A.S.M., 2012, Submarine transitional flow deposits in the Paleogene Gulf of

671   Mexico: Geology, *v.* 40, p. 1119-1122.

672   Kane, I., Pontén, A., Vangdal, B., Eggenhuisen, J., Hodgson, D.M. and Spychala, Y.T., in review, The

673   stratigraphic record and processes of turbidity current transformation across deep-marine lobes:

674   Sedimentology.

675

676   Kneller, B.C., and Branney, M.J., 1995, Sustained high-density turbidity currents and the deposition

677   of thick massive sands: Sedimentology, *v.* 42, p. 607-616.

678

679   Leclair, S.F., and Arnott, R.W.C., 2005, Parallel Lamination Formed by High-Density Turbidity

680   Currents: Journal of Sedimentary Research, *v.* 75, p. 1-5.

681

682   Levorsen, A.I., 1936, Structural versus structural accumulation: AAPG Bulletin, *v.* 20, p. 521-530.

683

684   Lowe, D.R., 1982, Sediment gravity flows: II. Depositional models with special reference to the

685   dposits of high-density turbidity currents: Journal of Sedimentary Petrology, *v.* 52, p. 279-297.

686

687   Lowe, D.R., and Guy, M., 2000, Slurry-flow deposits in the Britannia Formation (Lower Cretaceous),

688   North Sea: a new perspective on the turbidity current and debris flow problem: Sedimentology, *v.*

689   47, p. 31-70.

690

691   Luthi, S., 1981, Experiments on non-channelized turbidity currents and their deposits: Marine

692   Geology, *v.* 40, M59-M68.

693

694   Luthi, S.M., Hodgson, D.M., Geel, C.R., Flint, S.S., Goedbloed, J.W., Drinkwater, N.J., and

695   Johannessen, E.P., 2006, Contribution of research borehole data to modelling fine-grained turbidite

696   reservoir analogues, Permian Tanqua-Karoo basin-floor fans (South Africa): Petroleum Geosciences,

697   *v.*12, p. 175-190.

698

699   Macdonald, H.A., Peakall, J., Wignall, P.B., and Best, J., 2011, Sedimentation in deep-sea lobe

700   elements: implications for the origin of the thickening-upward sequences: Journal of the Geological

701   Society London, *v.* 168, p. 319-331.

702

703   MacPherson, B.A., 1978, Sedimentation and Trapping Mechanism in Upper Miocene Stevens and

704   Older Turbidite Fans of Southeastern San Joaquin Valley, California: AAPG Bulletin, *v.* 62, p. 2243-

705   2274.

706

707   Marchand, A.M.E., Apps, G., Li, W., and Rotzien, J.R., 2015, Depositional processes and impact on

708   reservoir quality in deepwater Paleogene reservoirs, US Gulf of Mexico: AAPG Bulletin, *v.* 99, p.

709   1635-1648.

710

711   Marini, M., Milli, S., and Moscatelli, M., 2011, Facies and architecture of the Lower Messinian

712   turbidite complexes from the Laga Basin (central Apennines, Italy): Journal of Mediterranean Earth

713   Science, *v.* 3, p. 45-72.

714   Marini, M., Salvatore, M., Ravnås, R., and Moscatelli, M., 2015, A comparative study of confined vs.

715   semi-confined turbidite lobes from the Lower Messinian Laga Basin (Central Apennines, Italy):

716   Implications for assessment of reservoir architecture: Marine and Petroleum Geology, *v.* 63, p. 142-

717   165.

718

719   Masalimova, L.U., Lowe, D.R., Sharman, G.R., King, P.R., and Arnot, M.J., 2016, Outcrop

720   characterization of a submarine channel-lobe complex: The Lower Mount Messenger Formation,

721   Taranaki Basin, New Zealand: Marine and Petroleum Geology, *v.* 71, p.360-390.

722

723   McCave, I.N., and Jones, K.P.N., 1988, Deposition of ungraded muds from high-density non-turbulent

724   turbidity currents: Nature, *v.* 333, p. 250-252.

725

726   Morris, W.R., Scheilhing, M.H., Wickens, DeV., Bouma, A.H., 2000, Reservoir architecture of

727   deepwater sandstones: examples from the Skoorsteenberg Formation, Tanqua Karoo Sub-Basin,

728   South Africa, *in* Weimer,P., Slatt, R.M., Bouma, A.H., and Lawrence, D.T., eds., Deep-water reservoirs

729   of the world: Gulf Coast Section SEPM Foundation, Twentieth Annual Research Conference, p. 1010-

730   1032.

731

732   Mutti, E., 1977, Distinctive thin-bedded turbidite facies and related depositional environments in the

733   Eocene Hecho Group (South-central Pyrenees, Spain): Sedimentology, *v.* 24, p. 107-131.

734

735   Mutti, E., 1992, Turbidite Sandstones. Instituto di Geologia, Università di Parma & AGIP, San Donato

736   Milanese, Italy, 275pp.

737

738   Nagatomo, A., and Archer, S., 2015, Termination geometries and reservoir properties of the Forties

739   Sandstone pinch-out, East Central Graben, UK North Sea, *in* McKie, T., Rose, P.T.S., Hartley, A.J.,

740   Jones, D.W., and Armstrong, T.L., eds., Tertiary Deep-Marine Reservoirs of the North Sea Region:

741   Geological Society London Special Publication, *v.* 403, p. 133-155.

742

743   Nelson, C.H., Twichell, D.C., Schwab, W.C., Lee, H.J., and Kenyon, N.H., 1992, Upper Pleistocene

744   turbidite sand beds and chaotic silt beds in the channelized, distal, outer-fan lobes of the Mississippi

745   fan: Geology, *v.* 20, p. 693–696.

746

747   Normark, W.R., 1978, Fan Valleys, Channels, and Depositional Lobes on Modern Submarine Fans:

748   Characters for Recognition of Sandy Turbidite Environments: AAPG Bulletin, *v.* 62, p. 912-931.

749

750   Patacci, M., Haughton, P.D.W., and McCaffrey, W.D., 2014, Rheological complexity in sediment

751   gravity flows forced to decelerate against a confining slope, Braux, SE France: Journal of Sedimentary

752   Research, *v.* 84, p. 270-277.

753

754   Pickering, K. T., 1981, Two types of outer fan lobe sequence, from the late Precambrian Kongsfjord

755   Formation submarine fan, Finnmark, North Norway: Journal of Sedimentary Research, *v.* 51, p. 1277-

756   1286.

757

758   Pickering, K. T., 1983, Transitional submarine fan deposits from the late Precambrian Kongsfjord

759   Formation submarine fan, NE Finnmark, N. Norway: Sedimentology, *v.* 30, 181-199.

760

761   Piper, D.J.W., and Normark, W.R., 1983, Turbidite depositional patterns and flow characteristics,

762   Navy Submarine Fan, California Borderland: Sedimentology, *v.* 30, p. 681-694.

763

764   Porten, K.W., Kane, I.A., Warchoł, M.J. and Southern, S.J., in press. A sedimentological process-based

765   approach to depositional reservoir quality of deep-marine sandstones: an example from the Springar

766   Formation, north-western Vøring Basin, Norwegian Sea. Journal of Sedimentary Research.

767

768   Prélat, A., Hodgson, D.M., and Flint, S.S., 2009, Evolution, architecture and hierarchy of distributary

769   deep-water deposits: a high-resolution outcrop investigation from the Permian Karoo Basin, South

770   Africa: Sedimentology, *v.* 56, p. 2132-2154.

771

772   Prélat, A., Covault, J.A., Hodgson, D.M., Fildani, A., and Flint S.S., 2010, Intrinsic controls on the range

773   of volumes, morphologies, and dimensions of submarine lobes: Sedimentary Geology, *v.* 232, p. 66-

774   76.

775

776   Prélat, A., and Hodgson, D.M., 2013, The full range of turbidite bed thickness patterns in submarine

777   lobes: controls and implications: Journal of the Geological Society London, *v.* 170, p. 1-6.

778

779   Pysklywec, R.N., and Mitrovica, J.X., 1999, The role of subduction-induced subsidence in the

780   evolution of the Karoo Basin: The Journal of Geology, *v.* 107, p. 155-164.

781

782   Rittenhouse, G., 1972, Stratigraphic-Trap Classification: Geologic Exploration Methods, *in* Gould,

783   H.R., ed., Stratigraphic Oil and Gas Fields—Classification, Exploration Methods, and Case Studies:

784   AAPG Memoir, *v.* 16, p. 14-28.

785

786   Rozman, D.J., 2000, Characterization of a Fine-Grained Outer Submarine Fan Deposit, Tanqua-Karoo

787   Basin, South Africa , *in* Bouma, A.H., and Stone, C.G., eds., Fine-grained Turbidite Systems: AAPG

788   Memoir 72/SEPM Special Publication, *v.* 68, p. 279-290.

789

790   Saller, A., Werner, K., Sugiaman, F., Cebastiant, A., May, R., Glenn, D., and Barker, C., 2008,

791   Characteristics of Pleistocene deep-water fan lobes and their application to an upper Miocene

792   reservoir model, offshore East Kalimantan, Indonesia: AAPG Bulletin, *v.* 92, p. 919–949.

793

794   Smith, R., 1987a, Structure and deformation history of the Central Wales Synclinorium, northeast

795   Dyfed: evidence for a long-lived basement structure: Geological Journal, *v.* 22, p.183-198.

796

797   Smith, R., 1987b, The *Griestoniensis* Zone Turbidite System, Welsh Basin, in Leggett, J.K. and Zuffa,

798   C.G., eds., Marine Clastic Sedimentology: Concepts and Case Studies: Graham & Trotman, London, p.

799   89-107.

800

801   Smith, R., 2004, Turbidite systems influenced by structurally induced topography in the multi-

802   sourced Welsh Basin, *in* Lomas, S.A. and Joseph, P., eds., Confined Turbidite Systems: Geological

803   Society London Special Publication, *v.* 222, p. 209-228.

804

805   Smith, R., and Joseph, P., 2004, Onlap stratal architectures in the Gres d'Annot: geometric models

806   and controlling factors, *in* Joseph, P. and Lomas, S.A., eds., Deep-Water Sedimentation in the Alpine

807   Basin of Se France: New Perspectives on the Gres d'Annot and related systems: Geological Society

808   London Special Publication, *v.* 221, p. 389-399.

809

810   Sømme, T.O., Helland-Hansen, W., Martinsen, O., and Thurmond, J.B., 2009, Relationships between

811   morphological and sedimentological parameters in source-to-sink systems: a basis for predicting

812   semi-quantitative characteristics in subsurface systems: Basin Research, *v.* 21, p. 361–387.

813

814   Southard, J.B., 1991, Experimental determination of bed-form stability: Annual Review of Earth and

815   Planetary Science, *v.* 19, p. 423-455.

816

817   Southern, S.J., Patacci, M., Felletti, F., and McCaffrey, W.D., 2015, Influence of flow containment and

818   substrate entrainment upon sandy hybrid event beds containing a co-genetic mud-clast rich division:

819   Sedimentary Geology, *v.* 321, p. 105-122.

820

821   Southern, S.J., Kane, I.A., Warchoł, M.J., Porten, K.W. and McCaffrey, W.D., 2016. Hybrid event beds

822   dominated by transitional-flow facies: Character, distribution and significance in the Maastrichtian

823   Springar Formation, north-west Vøring Basin, Norwegian Sea. Sedimentology, published online. DOI:

824   10.1111/sed.12323

825   Spychala, Y.T., Hodgson, D.M., Flint, S.S., and Mountney, N.P., 2015, Constraining the sedimentology

826   and stratigraphy of submarine intraslope lobe deposits using exhumed examples from the Karoo

827   Basin, South Africa: Sedimentary Geology, *v.* 322, p. 67-81.

828

829   Spychala, Y.T., Hodgson, D.M., Stevenson, C.J., and Flint, S.S., 2016, Aggradational lobe fringes: the

830   influence of subtle intrabasinal topography on sediment gravity flow processes and lobe stacking

831   patterns: Sedimentology, published online. DOI: 10.1111/sed.12315

832

833   Talling, P.J., Amy, L.A., Wynn, R.B., Peakall, J., and Robinson, M., 2004, Beds comprising debrite

834   sandwiched within co-genetic turbidite: origin and widespread occurrence in distal depositional

835   envrionments: Sedimentology, *v.* 51, p. 163-194.

836

837   Talling, P.J., Masson, D.G., Sumner, E.J., and Malgesini, G., 2012a, Subaqueous sediment density

838   flows: Depositional processes and deposit types: Sedimentology, *v.* 59, p. 1937-2003.

839

840   Talling, P.J., Malgesini, G., Sumner, E.J., Amy, L.A., Felletti, F., Blackbourn, G., Nutt, C., Wilcox, C.,

841   Harding, I.C., and Akbari, S., 2012b, Planform geometry, stacking pattern, and extrabasinal origin of

842   low strength and intermediate strength cohesive debris flow deposits in the Marnoso-arenacea

843   Formation, Italy: Geosphere, *v.* 8, p. 1207-1230.

844

845   Talling, P.J., 2013, Hybrid submarine flows comprising turbidity current and cohesive debris flow:

846   Deposits, theoretical and experimental analyses, and generalized models: Geosphere, *v.* 9, p. 460-

847   488.

848

849   Tankard, A., Welsink, H., Aukes, P., Newton, R., and Stettler, E., 2009, Tectonic evolution of the Cape

850   and Karoo basins of South Africa: Marine and Petroleum Geology, *v.* 26, p. 1379-1412.

851

852   Twichell, D.C., Schwab, W.C., Nelson, C.H., Kenyon, N.H., and Lee, H.J., 1992, Characteristics of a

853   sandy depositional lobe on the outer Mississippi fan from DeaMARC IA sidescan sonar images:

854   Geology, *v.* 20, p. 689–692.

855

856   Twichell, D.C., Cross, V.A., Hanson, A.D., Buck, B.J., Zybala, J.G., and Rudin, M.J., 2005, Seismic

857   architecture and lithofacies of turbidites in Lake Mead (Arizona and Nevada, U.S.A.), an analogue for

858   topographic complex basins: Journal of Sedimentary Research, *v.* 75, p. 134-148.

859

860   van der Werff, W., and Johnson, S., 2003a, High resolution stratigraphic analysis of a turbidite

861   system, Tanqua Karoo Basin, South Africa: Marine and Petroleum, Geology, *v.* 20, p. 45-69.

862

863   van der Werff, W., and Johnson, S., 2003b, Deep-sea fan pinch-out geometries and their relationship

864   to fan architecture, Tanqua Karoo basin (South Africa): Geologische Rundschau, *v.* 92, p. 728-742.

865

866   Visser, J.N.J., 1997, Deglaciation sequences in the Permo-Carboniferous Karoo and Kalahari basins of

867   the southern Africa: a tool in the analysis of cyclic glaciomarine basin fills: Sedimentology, *v.* 44, p.

868   507-521.

869

870   Visser, J.N.J, and Prackelt, H.E., 1996, Subduction, mega-shear systems and Late Palaeozoic basin

871   development in the African segment of Gondwana: Geologische Rundschau, *v.* 85, p. 632-646.

872

873   Wickens, H.d.V., 1994, Basin floor fan building turbidites of the southwestern Karoo Basin, Permian

874   Ecca Group. PhD Thesis, Port Elizabeth University, South Africa, 233pp.

875

876   Wickens, H.d.V., and Bouma, A.H., 2000, The Tanqua Fan Complex, Karoo Basin, South Africa –

877   outcrop analogue for fine-grained, deepwater deposits, *in* Bouma, A.H., and Stone, C.G., eds., Fine-

878   grained Turbidite Systems , AAPG Memoir 72/SEPM Special Publication, *v.* 68, p. 153–165.

879

880   Wild, R.J., Hodgson, D.M., and Flint, S.S., 2005, Architecture and stratigraphic evolution of multiple,

881   vertically-stacked slope-channel complexes, Tanqua depocentre, Karoo Basin, South Africa, *in*

882   Hodgson, D.M., and Flint, S.S., eds.*,* Submarine Slope Systems, Processes and Products: Geological

883   Society London Special Publication, *v.* 244, p. 89–112.

884

885   Wild, R., Flint, S.S., and Hodgson, D.M., 2009, Stratigraphic evolution of the upper slope and the shelf

886   edge in the Karoo Basin, South Africa. Basin Research, *v.* 21, p. 502-527.

887

888   Wilson, D., Davies, J.R., Waters, R.A., and Zalasiewicz, J.A., 1992, A fault-controlled depositional

889   model for the Aberystwyth Grits turbiditic system: Geological Magazine, 129, p. 595-607.

890

891 Wynn, R.B., Weaver, P.E., Masson, D.G., and Stow, D.A.V., 2002, Turbidite depositional architecture

892 across three interconnected deep-water basins on the north-west African margin: Sedimentology, *v.*

893 49, p. 669-695.
894

Figure Captions

896 Fig. 1: A: Simplified model indicating the different sub-environments in a lobe (redrawn from Prélat

897 et al., 2009). B: Plan-form view of five-fold lobe hierarchy: bed to bed set, lobe element, lobe, lobe

898 complex and lobe complex set (modified from Prélat et al., 2010).

899 Fig. 2: A: The Tanqua depocentre inboard of the Cape Fold Belt (Cederberg and Swartberg branches).

900 The square indicates the location of the study area. B: Stratigraphy of the Tanqua depocenter

901 (redrawn after Wild et al., 2009). The Skoorsteenberg Formation overlies the Tierberg Formation,

902 and is overlain by the Kookfontein Formation. This study focuses on Fan 4. Images taken from

903 Google Earth.

904 Fig. 3: Locations of recently cored wells, outcrops, NOMAD well locations used in the study. Fan 4

905 outcrops are marked in white. Images taken from Google Earth.

906 Fig. 4: Representative outcrop photographs of observed sedimentary facies. A: Structureless thick-

907 bedded sandstone (F1). Person for scale (~ 1.7 m); B: Structured medium-bedded sandstone (F2). C:

908 Hybrid bed (F4) with lower clean division and upper mudstone clast –rich division, Lens cover as

909 scale (~7 cm diameter); D: Thin-bedded heterolithic strata (F6). Logging pole for scale (10 cm

910 increments); E: Thin-bedded siltstone (F7) and mudstone. Lens cover for scale (~7 cm diameter); F:

911 Mudstone (F8) horizon overlain by sandstone. Logging pole for scale (10 cm increments).

912 Fig. 5: Representative core photographs of observed facies. A: Structureless sandstone (F1); B:

913 Structured sandstone (F2); C: Banded sandstone (F3); D: Hybrid bed (F4) with lower clean sandstone

914   division and upper argillaceous sandstone division; E: Debrites (F5); F: Heterolithic package (F6); G:

915   Siltstones (F7); H: mudstone (F8).

916   Fig. 6: Isopach and paleocurrent maps for A. Lower and B. Upper Fan 4. Contours are in meters.

917   Paleocurrent roses represent data collected during the study, whereas paleocurrent arrows

918   represent data from previous work based on Hodgson et al. (2006).

919   Fig. 7: Correlation panels of Fan 4. Top: Correlation of a S-N transect from Bloukop (BK) to Isle of Sky

920   (Ios). Bottom: SW-NE correlation from Klipfontein (Kf) to Isle of Sky (Ios). The base of the mudstone

921   and siltstone interval (black unit) that separates the Lower and Upper Fan 4 is used as a datum.

922   Pinchout of lobes 1-5 of the lower Fan 4 are indicated by black-arrows and their plan-view

923   distribution is shown in Figure 10.

924   Fig. 8: A: Hierarchical model of Fan 4. Location of panel is marked in Fig. 3. Fan 4 consists of two

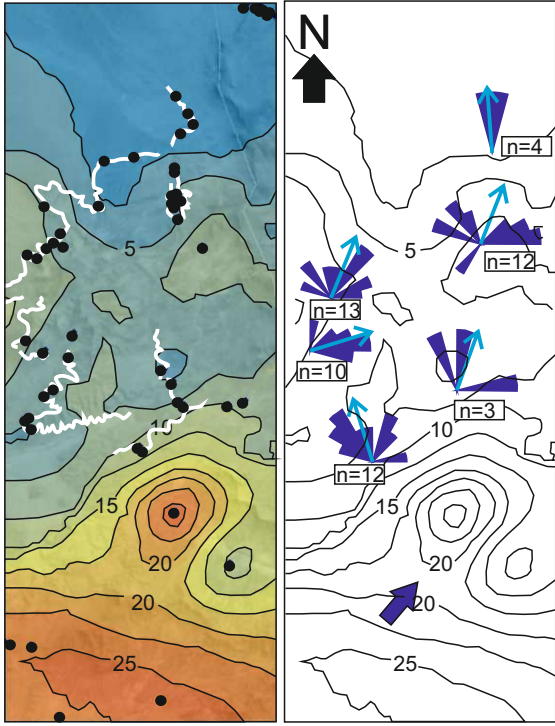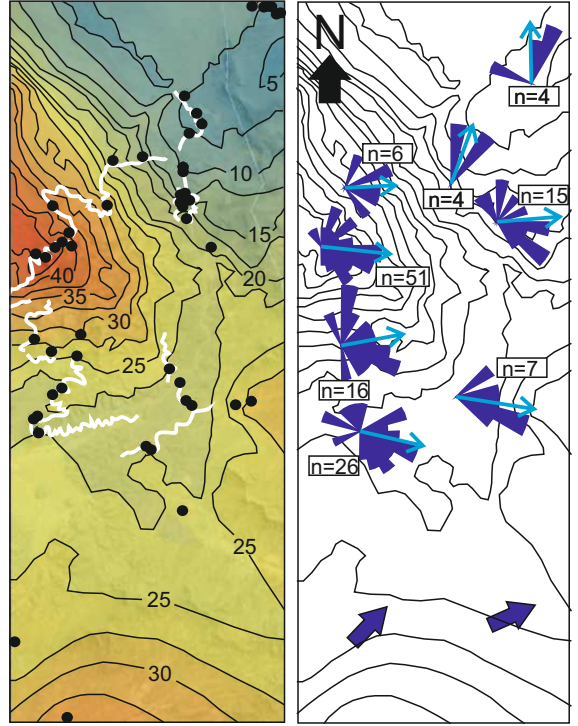925   sand-prone divisions that are separated by a thin-bedded heterolithic lobe fringe complex (LC2).

926   Lower Fan 4 comprises one lobe complex (LC1), and upper Fan 4 comprises two lobe complexes (LC3

927   and LC5) and a lobe complex fringe (LC4). Blue square marks zoom-in area of B and C. B: Close-up of

928   the LC2 deposits in the OR well (see Fig. 3 for location). C: Corresponding core photographs.

929   Fig. 9: Representative photographs of lobe successions in the field area. A: Lobe fringe deposits of

930   lower Fan 4 overlain by lobe axis and off-axis deposits of upper Fan 4. Person as scale (~1.7 m); B:

931   Lobe fringe deposits of lower Fan 4 overlain by lobe axis and off-axis deposits of upper Fan 4 C:

932   Lower Fan 4. Hybrid beds are separated by thin-bedded siltstone successions. Person as scale (~1.7

933   m). D: Thick-bedded lobe axis deposits of upper Fan 4. Person as scale (~1.7 m).

934   Fig. 10: Facies distributions and paleogeographic reconstruction for Lower Fan 4, which comprises

935   one lobe complex (LC1) that prograded northward. Black lines indicate the location of lobe-scale dip

936   and strike correlation panels in Figure 12. The green line indicates the location of the Los Kop

937   outcrop area of Hodgson et al. (2006), whereas blue and purple lines mark the location of

938   correlation panels in Figure 7, as do lobe numbers.

939   Fig. 11: Well core log through Fan 4(NS3; see Fig.2). The lower lobe complex of Fan 4 comprises

940   solely thin-bedded heterolithic deposits, siltstones and mudstones, which represents stacked lateral

941   lobe fringe successions. The upper division of Fan 4 shows consists of interbedded structureless

942   sandstone, hybrid beds and heterolithic packages.

943   Fig. 12: Dip and strike facies transitions in individual lobes within LC1 of Fan 4. A: Strike section in the

944   Gemsbok Valley (see Figure 10 for location). Lithology changes from structureless sandstone to

945   structured sandstone to heterolithic deposits. B: Dip section on the Sout Rivier area (see Figure 10

946   for location). Lithology is dominated by structureless sandstone, hybrid beds and siltstone.

947   Fig. 13: Correlation panels of stacked frontal lobe fringes around Katjiesberg in LC3. A: Location of

948   the correlation panels at Katjiesberg and paleogeography of the Upper Fan 4. B: Areal correlation of

949   four pinch-out fingers and zoom into the northwestern-southeastern part of the correlation panel

950   with sedimentary facies of the pinch-out fingers. They are composed of structureless sandstone

951   deposits, debrites and siltstone deposits.

952   Fig. 14: Representative lobe fringe photographs. A: Frontal lobe fringe deposits at Katjiesberg. B:

953   Frontal lobe fringe deposits at Katjiesberg. C: Lateral lobe fringe deposits at Klipfontein. Logging pole

954   for scale. D: Lateral lobe fringe deposits at Hammerkranz. Logging pole for scale.

955   Fig.15: A: Simplified anatomy of frontal lobe fringe deposits. B: Simplified anatomy of lateral lobe

956   fringe deposits. C: Example log showing a vertical section through a frontal lobe fringe in the Sout

957   River area. D: Example log showing a vertical section through a lateral lobe fringe in the Gemsbok

958   East core.

959   Fig. 16 A: Simplified plan view of a lobe marking the distribution of lobe sub-environments and

960   example logs for each sub-environment. B: Dominant flow processes to deposit frontal lobe fringes:

961   High-density turbidity currents and strongly stratified flows. C: Low-density turbidity currents and

962   debris flow deposit lateral lobe fringes. C is modified from Kane et al. (in press).

963   Table 1. Summary of sedimentary facies of Fan 4.

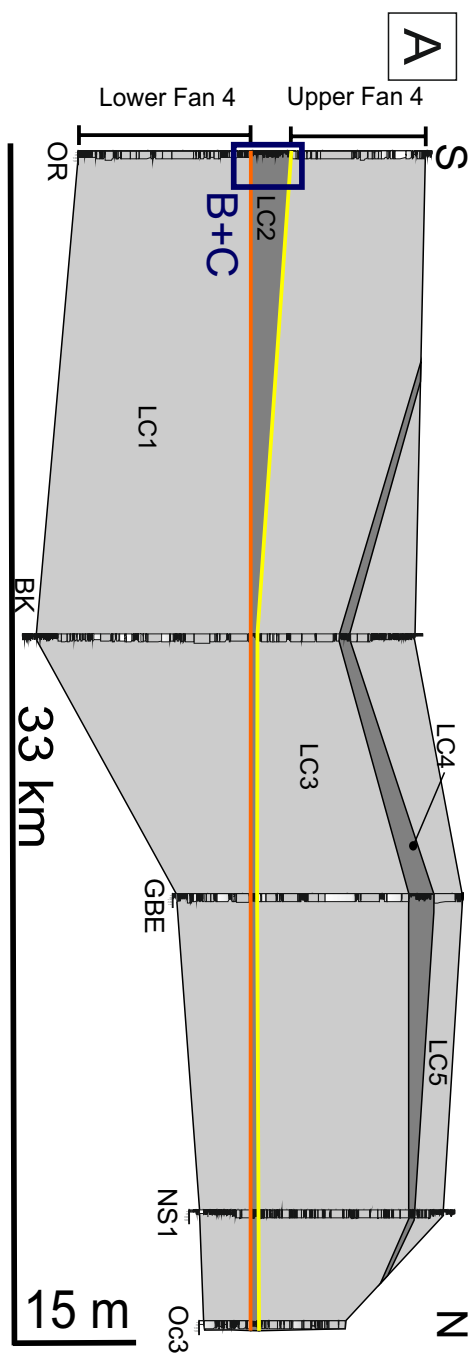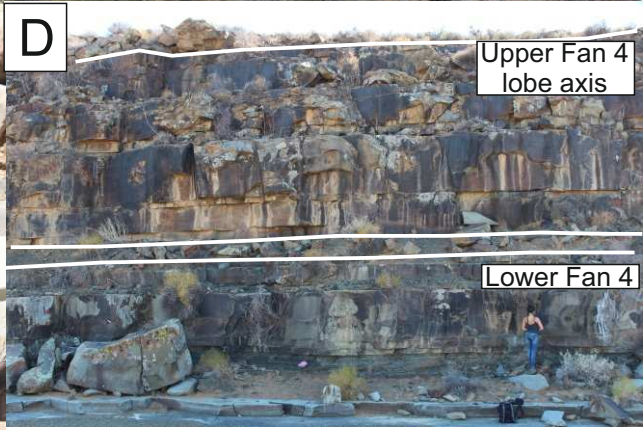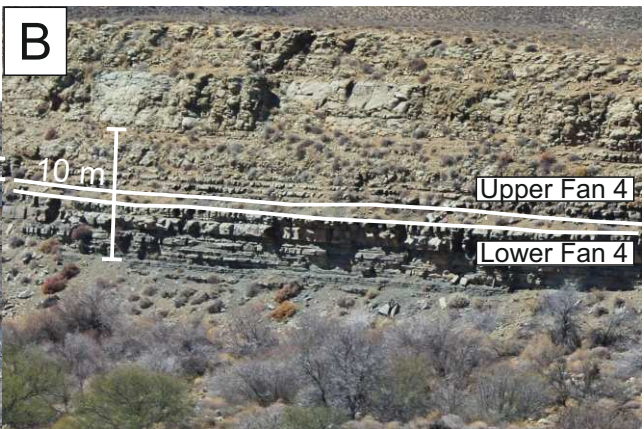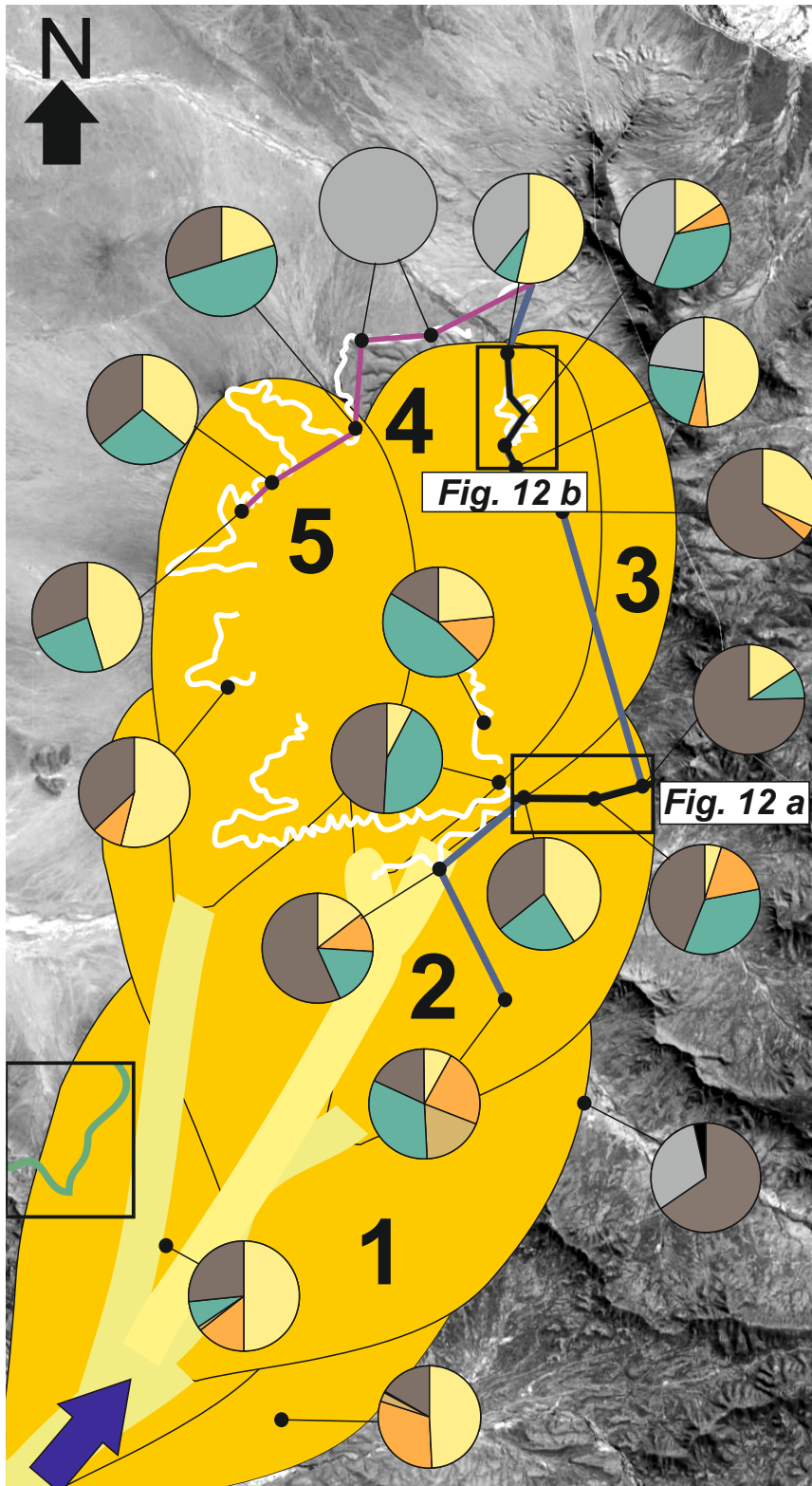964   Table 2. Recognition criteria of frontal and lateral lobes for outcrop and core.
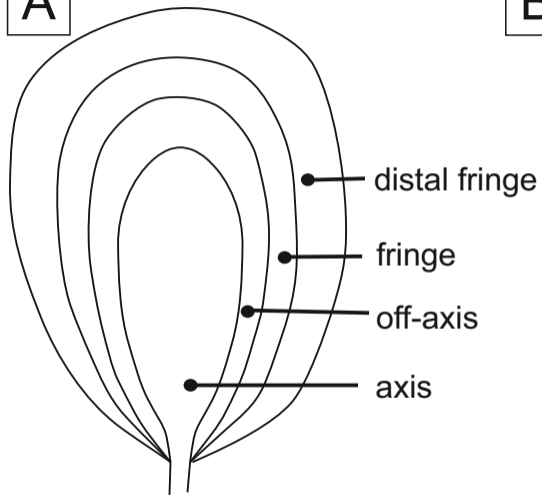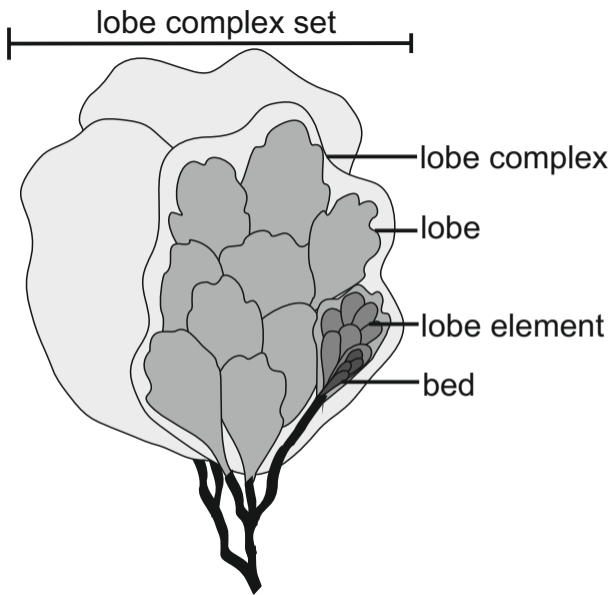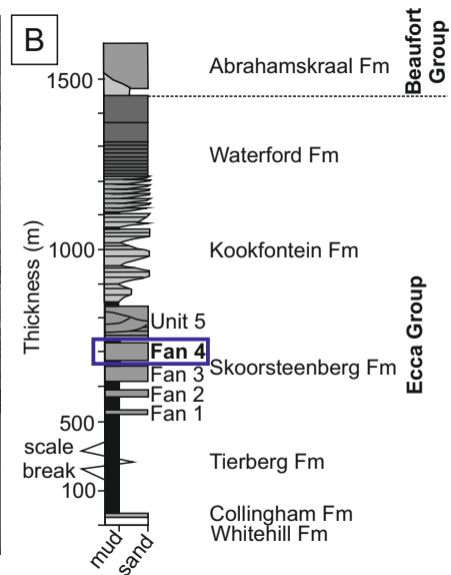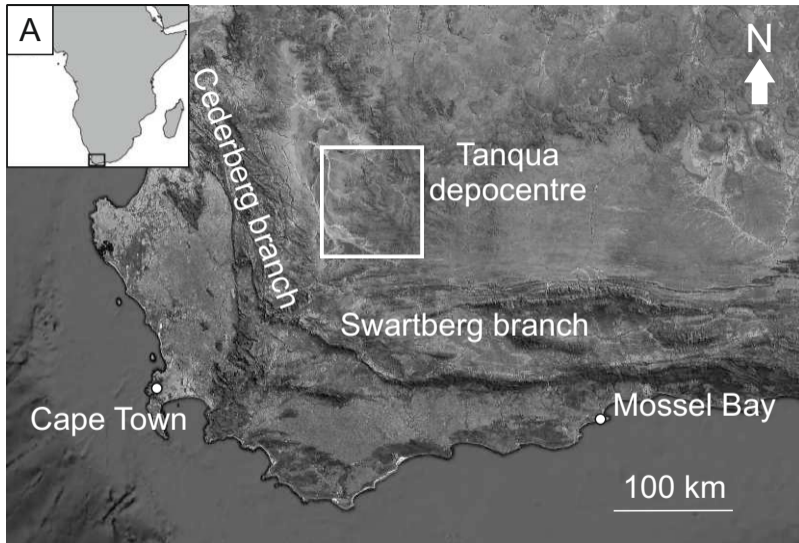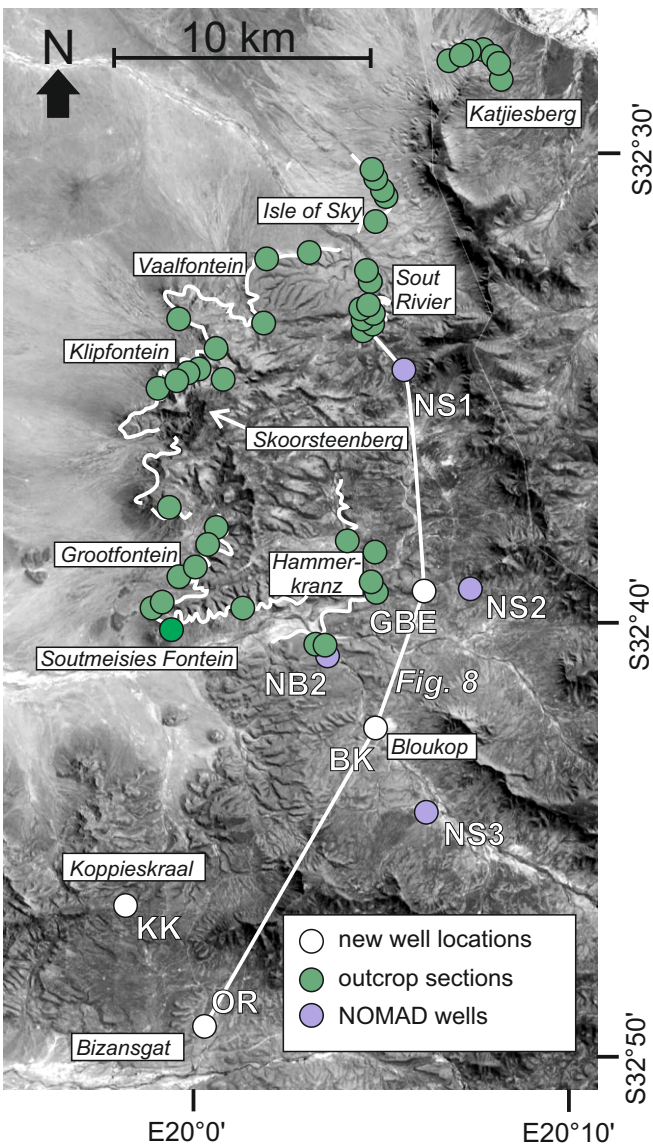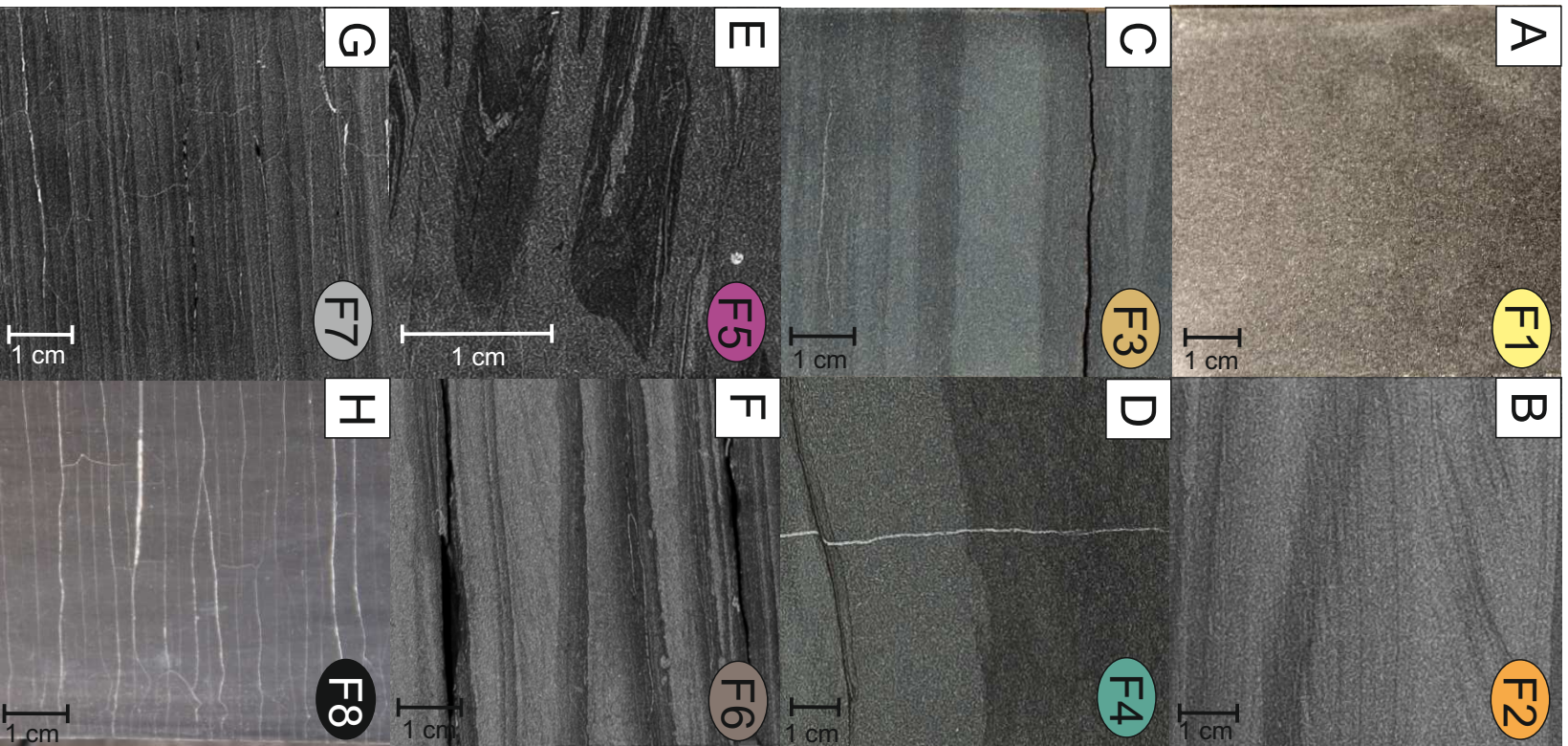
A Lower Fan 4

B Upper Fan 4

paleocurrent

paleocurrent (previous studies)

isopach (m)

10 km

A

S — N

31 km

20 m

Upper Fan 4

Lower Fan 4

Correlation of lobes not possible
due to distance of well locations and
juxtaposition of two coeval lobe
complexes (LC3)

Oc1 Oc4 Oc6

4 Ios4 Ios 2

1 Nb2 Hk2 GBE Ns2 **2** **?** Ns1 Oc2 Oc3 Oc5 Oc7 Ios5 Ios3 Ios1

3

BK

B

SW — NE

9 km

20 m

Upper Fan 4

LF4

5 Ios 6 Ios 7 Ios5

Kf1 Kf2 Kf3 Kf4 VF

N

NS1

GBE

NS2

NB2

BK NS3

10 km

Structureless sandstone (F1)	Banded sandstone (F3)	Heterolithic thin-beds (F6)
Structured sandstone (F2)	Hybrid beds (F4)	Siltstone (F7)

lobe pinchout

datum (LC2)

A — Upper Fan 4 / Lower Fan 4

B — 10 m / Upper Fan 4 / Lower Fan 4

C — Lower Fan 4

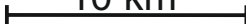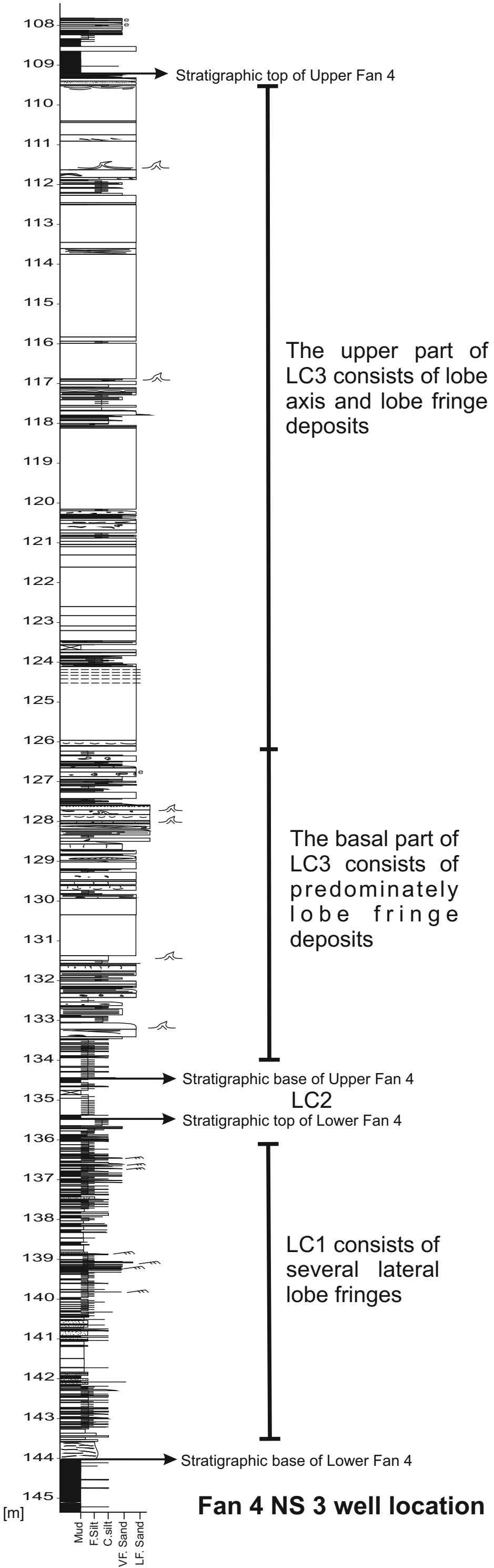D — Upper Fan 4 lobe axis / Lower Fan 4

Facies (piecharts)

- structureless sandstone (F1)
- structured sandstone (F2)
- banded sandstone (F3)
- hybrid beds (F4)
- heterolithic thin-beds (F6)
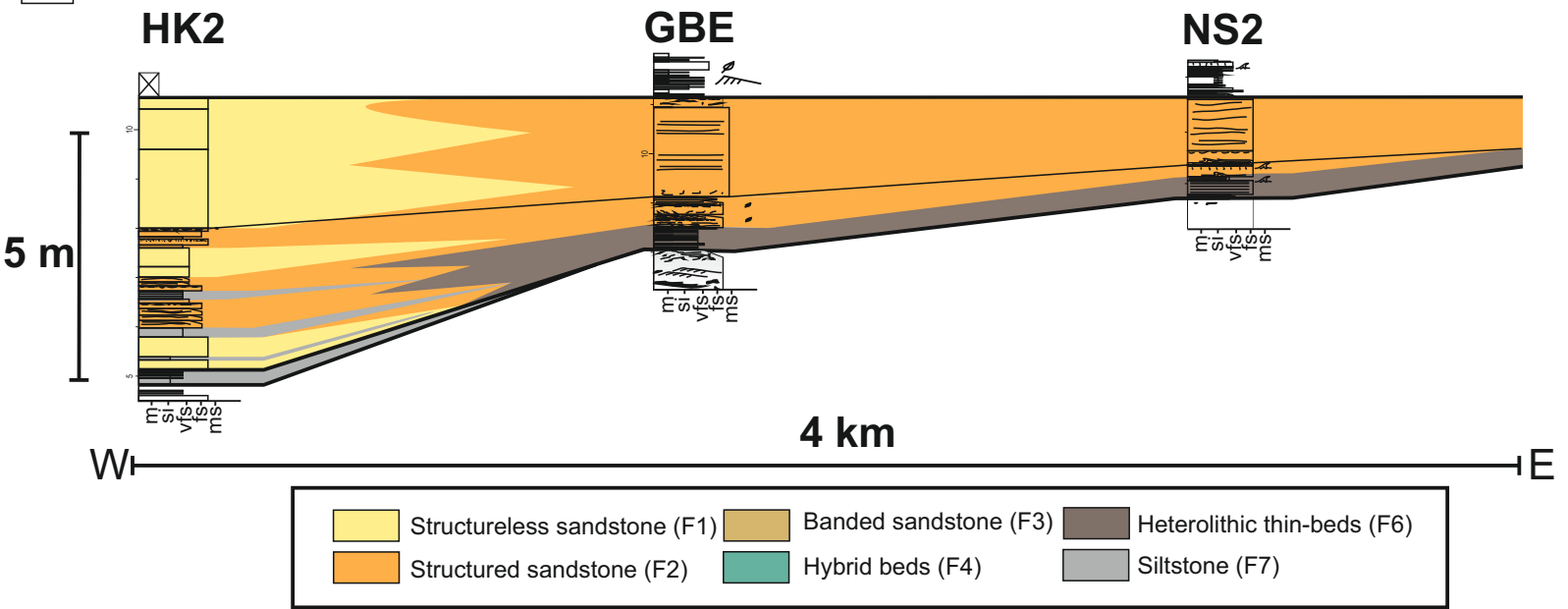- siltstone (F7)
- claystone (F8)

Lobe reconstruction

- mean paleocurrents
- corelation panels Fig. 12
- Los Kop outcrop
- S-N correlation panel (cf. Figure 7)
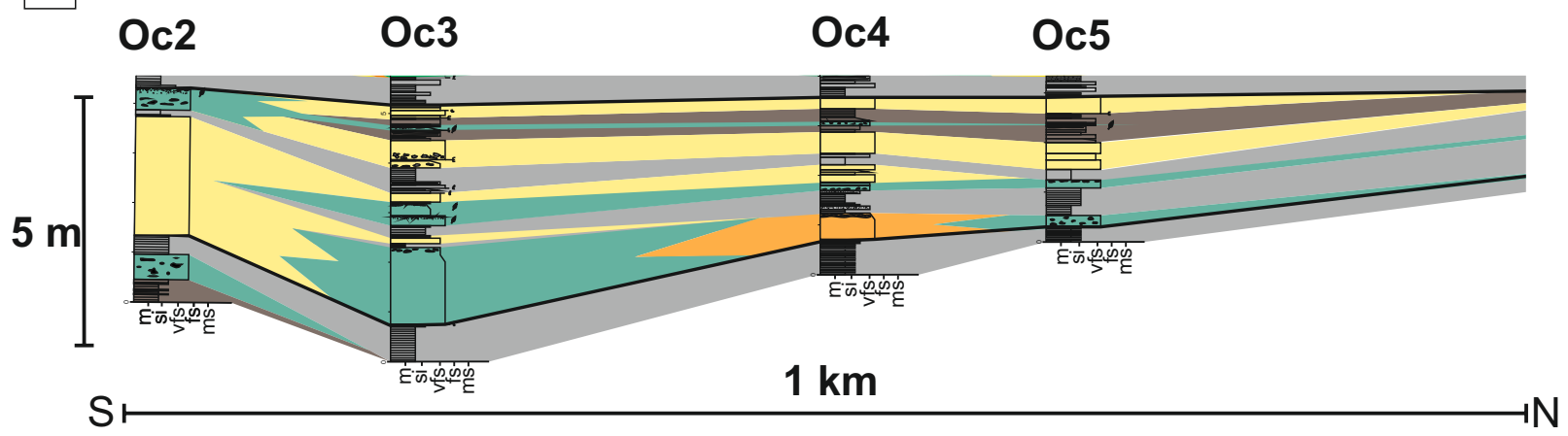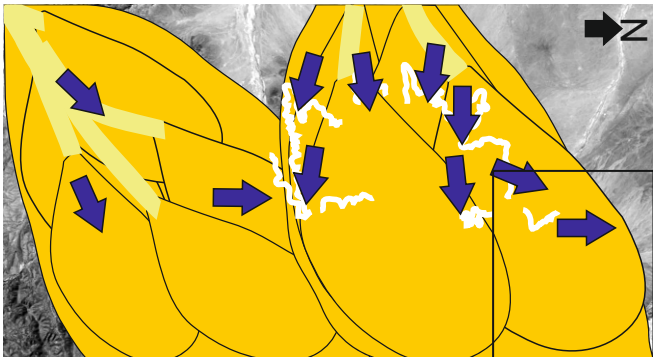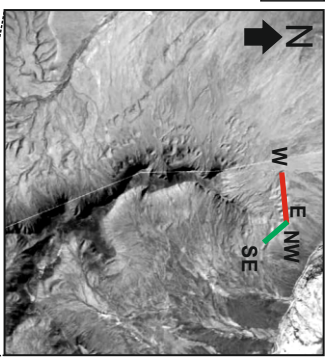- SW-NE correlation panel (cf. Figure 7)
- 1 lobe number (cf. Figure 7)

10 km

N

Fig. 12 b

Fig. 12 a

4

5

3

2

1

Stratigraphic top of Upper Fan 4

The upper part of LC3 consists of lobe axis and lobe fringe deposits

The basal part of LC3 consists of predominately lobe fringe deposits

Stratigraphic base of Upper Fan 4

LC2

Stratigraphic top of Lower Fan 4

LC1 consists of several lateral lobe fringes

Stratigraphic base of Lower Fan 4
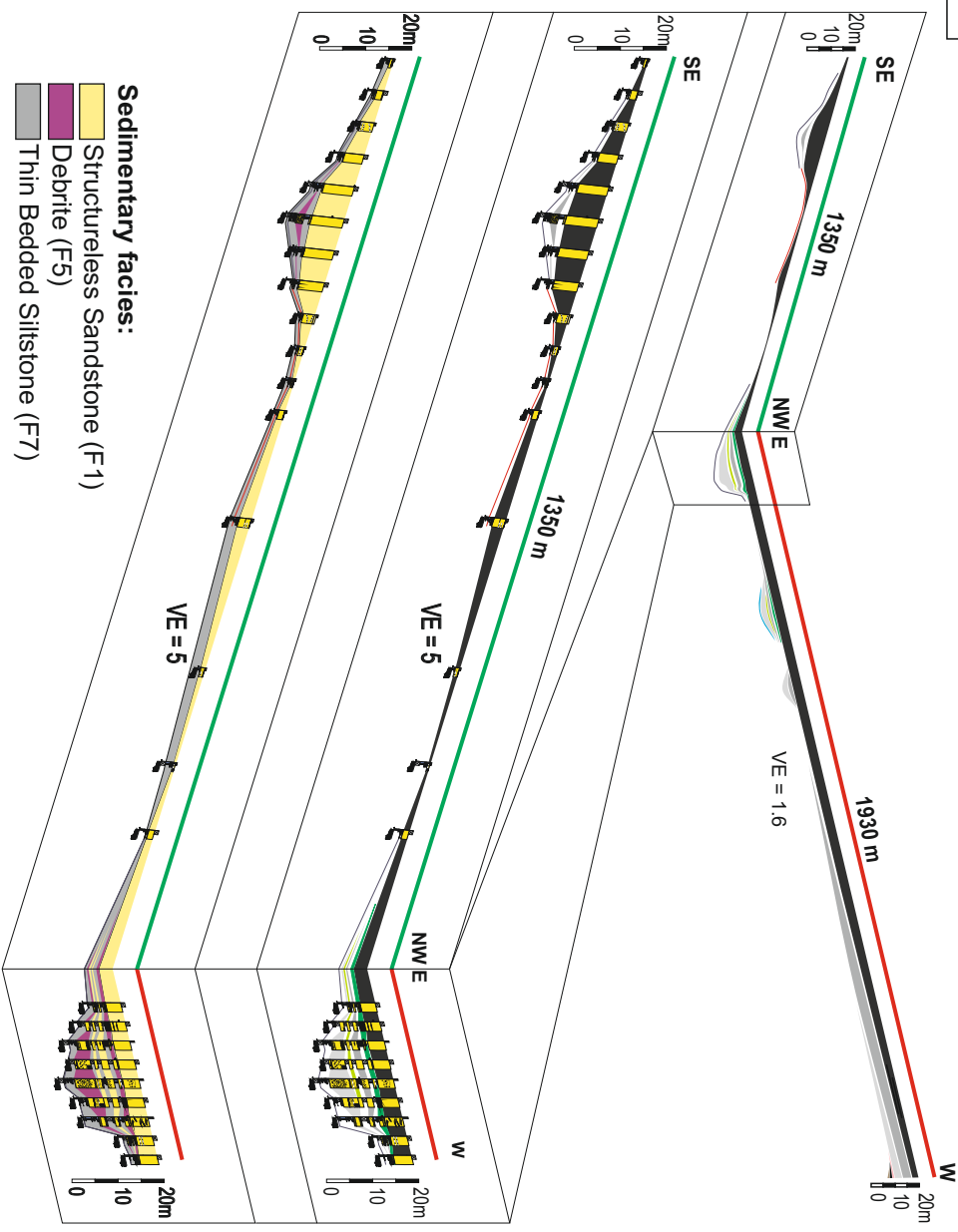
Fan 4 NS 3 well location

[m]

Mud F.Silt C.silt V.F. Sand L.F. Sand
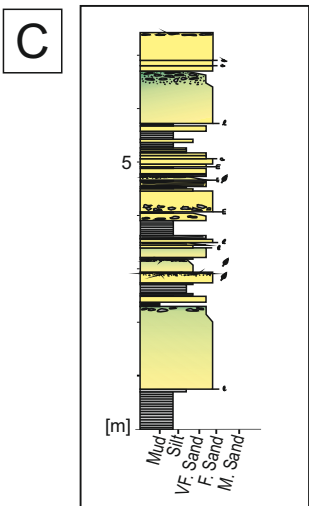
A Oblique strike section from Hammerkranz to NS2

HK2 GBE NS2

5 m

W — 4 km — E

Legend:
- Structureless sandstone (F1)
- Structured sandstone (F2)
- Banded sandstone (F3)
- Hybrid beds (F4)
- Heterolithic thin-beds (F6)
- Siltstone (F7)

B Dip section in the Sout Rivier area

Oc2 Oc3 Oc4 Oc5

5 m

S — 1 km — N

A

B

Sedimentary facies:

Structureless Sandstone (F1)

Debrite (F5)

Thin Bedded Siltstone (F7)

VE = 5

VE = 5

VE = 1.6

1350 m

1350 m

1930 m

SE

NW E

W

SE

NW E

W

NW E

W

20m

10

0

20m

10

0

20m

10

0

20m

10

0

20m

10

0

N

A — Lateral lobe fringe

B — Lateral lobe fringe

C — Frontal lobe fringe, 12 m, thinning

D — Frontal lobe fringe, 10 m, thinning

A

paleoflow ⟶

Approximate scale (m)

0   250   500

paleoflow ⟶

B

paleoflow ⊙

Approximate scale (m)

0   250   500

C

example log through Sout Rivier

Mud Silt V.F. Sand F. Sand M. Sand

D

example log through GBE

Mud Silt V.F. Sand F. Sand M. Sand
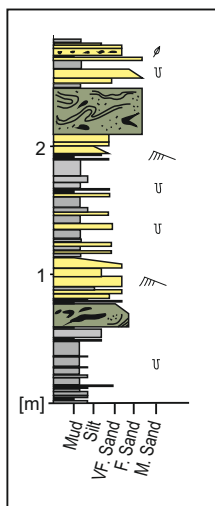
Lobe environments

- lobe axis
- lobe off-axis
- lobe fringe

Sedimentary facies

- sandstone
- siltstone
- debrite
- debritic divison
- claystone

A

Legend:
- axis
- off-axis
- lateral fringe
- frontal fringe
- distal fringe

B frontal fringe

high-density turbidity current

strongly stratified flow

C lateral fringe

low-density turbidity current

debris flow

Approximate scale (km)

0   1.5   3