

1 **Clastic injectites, internal structures and flow regime during injection: the**  
2 **Sea Lion Injectite System, North Falkland Basin**

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8 **ABSTRACT**

9 This paper details and describes a suite of 143 sub-seismic-scale clastic injectites encountered  
10 within the early Cretaceous, early post-rift of the deep-lacustrine North Falkland Basin. The  
11 injectites, referred to here as the Sea Lion Injectite System (SLIS), are encountered below,  
12 above and in-between the hydrocarbon-bearing, deep-lacustrine turbidite sandstones of the  
13 Bleaker 15, Sea Lion North, Sea Lion, Casper and Beverley fans. Sedimentary structures are  
14 documented within the injectites including: planar laminations, mud-clast imbrication and clast  
15 alignment. Clasts align along cm-scale foresets formed through ripple-scale bedform migration  
16 in a hydraulically-open fracture. The style of flow within the injectite system is interpreted as  
17 initially through fluid turbulence during an open fracture phase, which was followed by a later  
18 stage where laminar flow dominated, most likely during the closing phase of the fracture  
19 system. The host rocks display evidence for ductile deformation, which along with ptygmatic  
20 folding of dykes and internally injected mud-clasts, suggests a period of injection into relatively  
21 uncompact sediments. Evidence for brittle fracturing, in the form of stepped margins may be  
22 indicative of a separate phase of emplacement into more-compacted sediments. This variability  
23 in deformation styles is related to multi-phased injection episodes into host strata at different  
24 stages of consolidation and lithification at shallow burial depths. Injectites have been identified  
25 in four stratigraphic groupings: above the Bleaker 15 Fan and within/above the Sea Lion North  
26 Fan; within the hydrocarbon-bearing Sea Lion Fan; overlying the Sea Lion Fan; and  
27 above/below the hydrocarbon-bearing Casper and Beverley fans. This spatial association with  
28 the hydrocarbon-bearing fans of the North Falkland Basin is important, considering the ability  
29 of injectite networks to form effective fluid-flow conduits in the subsurface. Consequently, the  
30 findings of this study will improve the characterization of sub-seismic scale injectites (and  
31 therefore fluid conduits) within otherwise impermeable strata.

- 32 **Keywords:** Clastic injectites, Internal structures, Ripple cross-lamination, Fluid connectivity,  
33 Deep-lacustrine, North Falkland Basin

## 34 INTRODUCTION

35 Clastic injectites, also referred to as clastic dykes and sills, were first described by Murchison  
36 (1827) and have been widely recognised and described since the mid-1900s (Greensmith 1957;  
37 Peterson, 1968; Truswell, 1972; Hiscott, 1979; Dixon *et al.*, 1995). They are considered as  
38 natural examples of hydraulic fracturing (Lorenz *et al.*, 1991; Cosgrove, 2001; Jolly and  
39 Lonergan, 2002) because the process of their formation involves the pressure-driven injection  
40 of a fluid (a mix of clastic grains and water) into the surrounding material. In order for the  
41 injection to initiate, a pressure differential is required between, whereby the pore-fluid pressure  
42 exceeds the tensile strength of the host rock and the local confining stress oriented  
43 perpendicular to the fracture, causing fractures to initiate and propagate. Fracture propagation  
44 continues until the pressure dissipates, falling below the lithostatic pressure for sills, and below  
45 that of the minimum horizontal stress for the whole hydrofracture system (Jolly and Lonergan,  
46 2002; Vigorito and Hurst, 2010).

47 Large-scale clastic injectites (*c.* 10–100 m in width) have been targeted for hydrocarbon  
48 exploration as remobilized sands can act as excellent hydrocarbon reservoirs (Hurst *et al.*,  
49 2005; Hurst and Cartwright, 2007; Szarawarska *et al.*, 2010); and their potential to act as fluid  
50 conduits within otherwise low-permeability strata is well documented (e.g. Hurst *et al.*, 2003b;  
51 Jonk *et al.*, 2003; Mazzini *et al.*, 2003; Hurst *et al.*, 2011). A number of publications have  
52 described the global distribution of injectites, at various scales (Huuse *et al.*, 2010; Hurst *et al.*,  
53 2011, and references therein). The larger-scale structures have been well documented and  
54 described in terms of seismic-scale geometries (Hubbard *et al.*, 2007; Vigorito and Hurst, 2010;  
55 Scott *et al.*, 2013; Hurst and Vigorito, 2017).

56 The smaller scale features (*c.* 0.1 cm–10 m in width) can provide additional information  
57 concerning the sedimentary processes and flow rheology operating within fracture networks.  
58 Smaller scale injectites have been documented in core data (Duranti *et al.*, 2002; Duranti and  
59 Hurst, 2004; Hurst *et al.*, 2011 and references therein) and in outcrop (Rowe *et al.*, 2002; Hurst  
60 *et al.*, 2011 and references therein; Ravier *et al.*, 2015; Cobain *et al.*, 2015; 2017), where  
61 insights into their spatial, geometrical and sedimentological characteristics can be assessed.

62 Clastic injectites have been described in detail from outcrop in the Karoo Basin, South  
63 Africa (10s of cm wide dykes and up to 1.3 m thick sills; Cobain *et al.*, 2015; 2017), where  
64 remobilized sand sourced from deep-water lobe deposits has intruded into overlying and  
65 underlying hemi-pelagic mudstones. In this example, a suite of structures was observed

66 developed at the margins of injectites, including plumose ridges and ridged margins.  
67 Furthermore, excellent examples of clastic dyke and sill systems are also documented from the  
68 Aptian to Albian sedimentary fill of the Vocontian Basin, France (<0.5 m wide dykes and up  
69 to 6 m thick sills; Monnier *et al.*, 2015; Ravier *et al.*, 2015), the Hind Sandstone Member of  
70 the Carboniferous Craven Basin (<1 m wide dykes and up to 2 m thick sills; Kane, 2010), the  
71 upper Tortonian Marnoso-arenacea Formation, northern Italy (10–30 cm wide dykes; Gamberi,  
72 2010), and the Cretaceous–Palaeocene Moreno Formation of the Panoche and Tumney Hills,  
73 California, USA (up to 18 m wide dykes; Vigorito *et al.*, 2008; Hurst *et al.*, 2011 and references  
74 therein; Scott *et al.*, 2013; Hurst and Vigorito, 2017).

75 In subsurface datasets, core penetrations offer laterally-limited, but useful snapshots into the  
76 style of intrusion and sedimentological characteristics of clastic injectites. They have been  
77 documented within core data from the North Sea (UKCS), including, the Alba and Penguin  
78 fields (Hurst and Cartwright, 2007; ), the Tertiary reservoirs of the South Viking Graben (Jonk  
79 *et al.*, 2005a), the Gryphon Field (Newman *et al.*, 1993; Mazzini *et al.*, 2003); the intra-  
80 Paleogene Hamsun Prospect, Norway (de Boer *et al.*, 2007); the Nini Field, Eastern North Sea  
81 (Svendsen *et al.*, 2010), and the lower Palaeogene (Szarawarska *et al.*, 2010). Injectites have  
82 been sparsely documented in lacustrine sedimentary basins, with examples from the Dinantian  
83 sediments of the Midland Valley of Scotland (Greensmith, 1957; Jonk *et al.*, 2005b; Jonk *et*  
84 *al.*, 2007), the Eocene Green River Formation, Wyoming, USA (Töro and Pratt, 2015; 2016),  
85 and the Triassic strata of the Ordos Basin, central China (Gao *et al.*, 2019).

86 This work describes a series of clastic injectites that have been identified in conventional  
87 core data within, and in close proximity to, the Sea Lion Fan (and other fans) in the North  
88 Falkland Basin. Whilst the presence of these injectites has been mentioned briefly in the  
89 literature (Williams, 2015), they have not been described and documented in detail, or  
90 interpreted in terms of their probable genesis. A total of 143 sill and dyke-type injectites are  
91 identified within 455 m of conventional core data. Of the 143 injectites, 55 are discordant  
92 features, whilst 88 form concordant bodies. The injectites are observed both within and  
93 between deep-lacustrine turbidite fan deposits. Collectively, these injectites are referred to as  
94 the ‘Sea Lion Injectite System’ (SLIS), which describes all injectite features observed in the  
95 direct vicinity of the Sea Lion Fan, and includes those observed in overlying or adjacent  
96 depositional fan bodies. In documenting and describing the injectites of the SLIS, the following  
97 questions are addressed:

- 98 i.) Do sedimentary structures observed internally within the injectites of the SLIS  
99 reflect deposition by laminar or turbulent flow within the fracture network?  
100 ii.) What is the character of the host rock during the emplacement of the SLIS?  
101 iii.) What are the stratal relationships between the SLIS and the Sea Lion Fan (and  
102 other fans)?  
103 iv.) What was the timing, injection depth and the primer/triggering mechanism?  
104 v.) How might their presence impact fluid flow in the subsurface and associated  
105 hydrocarbon reservoir modelling?

106 Through this analysis, this study on sub-seismic-scale injectites adds not only to the general  
107 understanding of flow processes during injectite emplacement, but also to the relationships  
108 between injectites and the parent sands, and comments upon their potential to act as effective  
109 fluid conduits in the subsurface.

## 110 **GEOLOGICAL SETTING**

111 The North Falkland Basin, a Mesozoic-aged sedimentary basin located north of the Falkland  
112 Islands (Fig. 1), is a failed rift system comprising a series of offset depocentres following two  
113 dominant structural trends: north-south oriented faulting is predominant in the basin's northern  
114 area whilst significant NW-SE oriented faults control the south. The northern part of the basin  
115 has a half-graben geometry with the depocentre-controlling faults located on its eastern margin  
116 (Richards *et al.*, 1996a and 1996b; Richards and Fannin, 1997; Richards and Hillier, 2000a;  
117 Lohr and Underhill, 2015; Jones *et al.*, 2019). Rifting probably initiated in the the Jurassic  
118 period, and into the early Cretaceous, with some elements of the North Falkland Basin forming  
119 as a failed rift arm associated with the opening of the South Atlantic Ocean. The Eastern and  
120 Western grabens, which form the central rift system, are approximately 250 km long, from  
121 north to south, and 100 km wide from west to east, with a number of laterally-adjacent sub-  
122 basins that remain poorly understood (i.e. the Phyllis Graben; Fig. 1). Subsequently, the basin  
123 underwent a thermal sag phase that initiated during Berriasian–Valanginian times, forming the  
124 Transitional Unit (of Richards and Hillier, 2000a). This was followed by the deposition of a  
125 >1 km thick, early post-rift package, comprising the early Cretaceous-aged LC2–LC4 tectono-  
126 stratigraphical sub-units (as defined in Richards and Hillier, 2000a; Figs 2 and 3). The early  
127 post-rift is overlain by a thick middle post-rift unit (Richards and Hillier, 2000a), which forms  
128 a competent sealing lithology for the hydrocarbon system in the North Falkland Basin. It is  
129 within the LC3 sub-unit that the Sea Lion North, Sea Lion and Otter fans (Fig. 4A) were

130 deposited along the eastern margin of the North Falkland Basin (Dodd *et al.*, 2019), along with  
131 laterally adjacent turbidite systems of the Casper and Beverley fans (Bunt, 2015).

132 The Sea Lion Fan was first drilled by Rockhopper Exploration in 2010 and was declared as  
133 an oil discovery later that year (MacAulay, 2015). The Sea Lion Fan is composed of three  
134 lobes: Sea Lion 10 (SL10); Sea Lion 15 (SL15); and Sea Lion 20 (SL20). The lobes form a  
135 series of compensationally-offset stacked, tabular deposits (Figs 4B and 4C), that exhibit a  
136 complex suite of seismic amplitude architectures in plan view (as described in Dodd *et al.*,  
137 2019). Internally, the lobes comprise a series of high density turbidites, low density turbidites  
138 and hybrid event beds, interbedded within an otherwise hemi-limnic mudstone succession  
139 (Dodd *et al.*, 2019). This heterolithic succession, along with other fans and intervening  
140 mudstones in LC2 and LC3 (Bleaker 15, Sea Lion North, Casper and Beverley), were intruded  
141 into by a suite of clastic injectites that form the main focus of this study.

## 142 **METHODS AND DATASETS**

143 This study examines the relationship of 143 clastic injectites and their host strata from 455 m  
144 of non-oriented, vertically sliced, conventional core held as part of the Falkland Islands  
145 National Archive by the British Geological Survey. This dataset is supplemented by high-  
146 quality core photographs taken shortly after the 2010–2011 appraisal drilling of the Sea Lion  
147 Fan. During examination of the conventional core data and photographs, observations were  
148 made of injectite margin geometries, sedimentary structures and textures. These data have been  
149 augmented by a suite of high-quality down-hole wireline and sedimentary log data, which has  
150 been examined to determine the vertical and lateral spatial relationships between clastic  
151 injectites and the depositional sediments. Dyke and sill core plug porosity and permeability  
152 data have been provided (where available), which have been analysed, along with plotted dyke  
153 and sill geometrical information, in order to better assess potential impact of sub-seismic-scale  
154 injectites on hydrocarbon exploration and modelling.

### 155 ***Diagnostic features for clastic injectite identification***

156 Diagnostic features can be split into three categories: the relationship of the injectite with host  
157 rocks (discordance); structures that formed externally, as impressions or erosional features  
158 within the host lithologies (Scott *et al.*, 2009; Kane, 2010; Hurst *et al.*, 2011; Cobain *et al.*,  
159 2015), which are challenging to identify at core scale; and structures that are formed internally  
160 within the injectite bodies during flow into the fracture. Ideally, a combination of these

161 observations leads to a more accurate interpretation of sandstone bodies as either remobilized  
162 clastic injectites or sediments of primary deposition.

### 163 *Host rock relationships*

164 The presence of cross-cutting geometries, whereby sub-horizontal to vertical ( $>15\text{--}90^\circ$ )  
165 features discordantly intersect primary bedding, is the most reliable method for identifying  
166 injectites. Alternative nomenclature has previously been used to describe intrusions at shallow  
167 angles, for example ‘offshoots’ ( $<25^\circ$ ; Truswell, 1972; Hiscott, 1979), or ‘wings’ (15–40°;  
168 Kane, 2010) that are more typically observed emanating from the edges of larger scale  
169 depositional sand bodies in seismic data (Hurst *et al.*, 2003a; Huuse *et al.*, 2007). In this study,  
170 any feature that ranges in dip between  $>15^\circ$  and  $90^\circ$ , with respect to depositional bedding, is,  
171 for simplicity, termed a dyke.

172 Deformation of host rock lithologies can provide important information concerning  
173 emplacement timing, injection direction and characterization (*sensu* Kane, 2010; Ravier *et al.*,  
174 2015). Injectite emplacement can affect host rock lithologies either through syn-intrusion  
175 deformation (Rowe *et al.*, 2002; Goździk and Van Loom, 2007; Ravier *et al.*, 2015),  
176 particularly during more ductile emplacement, or through post-intrusion differential  
177 compaction of mudstone in the host rock around the more competent sandstones (Hiscott, 1979;  
178 Kane, 2010).

179 Clastic sills are horizontal or slightly inclined ( $<15^\circ$  relative to bedding) and are more  
180 challenging to identify than clastic dykes. One particular diagnostic feature of a clastic sill is  
181 stepped margins, or ‘step-ramp-step’ geometries (Cobain *et al.*, 2015). These geometries are  
182 observed at a range of scales, in a number of different settings, in both clastic intrusions  
183 (Duranti *et al.*, 2002; Vétel and Cartwright, 2010; Hurst *et al.*, 2011; Cobain *et al.*, 2015; Hurst  
184 and Vigorito, 2017) and igneous intrusions (Pollard *et al.*, 1975; Thomson and Hutton, 2004;  
185 Schofield *et al.*, 2012). They form as the tips of intrusions become offset or segmented during  
186 propagation (Schofield *et al.*, 2012), resulting in sills that appear, in strike-section, to step up  
187 or down stratigraphy. Stepped margins, in-particular upper margins, with steep, regularly  
188 spaced steps, are unlikely to have formed through depositional sedimentary processes.

### 189 *External features*

190 Clastic injectites display a range of structures at their margins, including undulation crests  
191 (Kane, 2010), flute marks, grooves, rills, lobate-scours, frondescent marks and gutter marks

192 (Hurst *et al.*, 2011 and references therein). In addition, they may have either smooth surfaces,  
193 blistered surfaces, plumose ridges or ridged margins (Cobain *et al.*, 2015). This suite of margin  
194 structures, created as erosional features or impressions within the host rock, are observed  
195 typically at the outcrop-scale and can be extremely challenging to identify at core-scale.

#### 196 *Internal features*

197 Internal features have been widely reported from examples of injectites, including: laminations;  
198 banding/layering/depositional layering; normal and reverse grading; aligned, sometimes  
199 imbricated, angular to rounded mud-clasts; ripple marks; and structureless (sandstone;  
200 ‘Appendix A’ in Hurst *et al.*, 2011, and references therein). Laminations develop within clastic  
201 dykes (Hubbard *et al.*, 2007), often oriented parallel with margins, and are formed through the  
202 alignment and sorting of tabular grains within the sandstone (Peterson, 1968; Hannum, 1980;  
203 Taylor, 1982). Layering (Peterson, 1968), depositional layering (Hillier and Cosgrove, 2002),  
204 banding (horizontal, inclined and vertical; Scott *et al.*, 2009) or flow banding (Kane, 2010) is  
205 represented by multiple ‘bands’ of different grain sizes within a single dyke. Normal and  
206 reverse grading occurs either perpendicular to, or along the length of, dyke margins (Hurst *et*  
207 *al.*, 2011) and can form repeated bands (Peterson, 1968). Mud-clasts are commonly  
208 encountered within injectites, and are often aligned with dyke walls and sometimes display  
209 imbrication (Kawakami and Kawamura, 2002; Kane, 2010). There are only limited references  
210 to ‘ripples’ in clastic injectites (Smyers and Peterson, 1971; Van der Meer *et al.*, 2009; Phillips  
211 *et al.*, 2013). Despite the description of all these structures within the literature, a general  
212 absence of sedimentary structures (structureless) is the most common attribute found in  
213 remobilized sandstones (Hurst *et al.*, 2003a; Hurst *et al.*, 2011 and references therein; Cobain  
214 *et al.*, 2015).

#### 215 *Limitations of core data*

216 The one-dimensional nature of subsurface core-data leads to difficulties in accurately  
217 distinguishing the genesis of bedding-concordant, structureless sandstone bodies. In particular,  
218 high-concentration sediment gravity flows, such as a high-density turbidity currents form  
219 thickly bedded, structureless sediments in deep-water environments (Lowe, 1979). These flows  
220 often deposit structureless, tabular sandstones, which are occasionally laminated and are  
221 normally graded. These depositional sandstones can appear almost identical to clastic sills  
222 formed through the intrusion of remobilized sand.



223 The identification of injectites around the Sea Lion Fan is further complicated by the limited  
224 number of wells that are cored. Furthermore, the vertical nature of 1D core data means that  
225 horizontal intrusions (sills) are more likely to be intersected than vertical features (dykes),  
226 particularly when the majority of dykes are thinner than that of the core barrel width. Finally,  
227 given the injectites are below the resolution of modern 3D seismic data (injectite maximum  
228 thicknesses of <70 cm, versus a seismic resolution of >12.5 m, at *c.* 2500 m TVDSS), it is  
229 challenging to characterize their distribution away from the cored well locations.

230 Despite these reservations and limitations, and taking into account the relatively small  
231 diameter of the core data (*c.* 12 cm), 143 injectites have been recognised in the 455 m of cored  
232 section. The relatively high intersection density (on average an injectite every three metres)  
233 may suggest that the injectites are laterally pervasive in the area around the Bleaker 15, Sea  
234 Lion North, Sea Lion, Casper and Beverley fans.

## 235 **CLASTIC DYKES**

### 236 **Description**

237 The clastic dykes in the SLIS comprise fine to medium-grained, sub-angular, well-sorted,  
238 quartz-rich, sandstones that form slightly inclined ( $>15^\circ$  with respect to bedding) to vertical  
239 structures that cross-cut primary bedding (Fig. 5). The sandstones are variably cemented, with  
240 some examples displaying a pervasive cement (Fig. 5A), whilst others show visible porosity  
241 (Figs 5B and 5C) and oil-staining (Fig. 5D). The width of clastic dykes ranges from 0.3–  
242 11.2 cm, with a modal width of 2.5 cm. They extend vertically through the core, reaching  
243 heights of between 0.5–82.0 cm, with a modal height of 5 cm. They often appear feeding to, or  
244 from, clastic sills (Fig. 6). Margin geometries can be: smooth (Fig. 5A); cusped with ‘pod-  
245 like’ lobate structures at varying scales (Fig. 5B); or jagged (Fig. 5C).

246 The dykes form a wide variety of contorted geometries, where sand thicknesses and the  
247 angle of discordance vary greatly (Figs 5A and 5B). The discordant bodies appear to plastically  
248 deform the host mudstones into which they are emplaced (Fig. 5B) and occasionally are  
249 observed alongside syn-sedimentary faulting or reverse displacements within host strata (Fig.  
250 6B). In particular, primary depositional laminations within the host rocks are deformed in a  
251 ductile or plastic manner (Fig. 6), and are offset by, or around, the emplaced sand (Figs 5B and  
252 6B).

253 A high proportion of the clastic dykes (57%) contain mud-clasts (Fig. 5) that typically have  
254 long-axis ranging between 0.5–5 cm and are angular, irregular or ‘torn’/rhomboid in shape.  
255 The mud-clasts are typically sorted into similar-sized clast populations. Despite most mud-  
256 clasts ranging between 0.5–5 cm long there are a few examples of beds that contain much  
257 smaller clasts, ranging between 0.1–0.5 cm wide, forming a ‘speckled texture’ within the  
258 injectite (Fig. 5C; in this example the mud-clasts also display an alignment). Alignment is also  
259 observed in a number of other examples (Figs 5A, 5B and 5D), where elongate mud-clasts are  
260 oriented perpendicular or sub-perpendicular to the long-axis of the dyke margin.

## 261 **Interpretation**

262 The fine to medium-grade grain sizes are in keeping with grades known to preferentially-  
263 fluidize and re-mobilize (Lowe, 1975). The observation of clastic dykes feeding to, or from,  
264 clastic sills (Fig. 6), indicates a relationship between the two, suggesting they were coeval. The  
265 cross-cutting relationship between the dykes and the primary sedimentary bedding  
266 demonstrates that dyke emplacement occurred after the deposition of the lacustrine mudstones  
267 and turbidite sandstones (and therefore injection was not syn-depositional with those units).

268 The contorted geometries observed in some of the clastic dykes (Figs 5A and 5B) are  
269 interpreted as examples of ptygmatic folding (*sensu* Kuenen, 1968). Ptygmatic folding of  
270 clastic dykes has been associated with post-intrusion compaction of intruded host rocks,  
271 resulting in the compression of originally straight clastic dykes into folded structures (Hiscott,  
272 1979; Duranti and Hurst, 2004; Parize *et al.*, 2007). The necessity to first intrude the host rocks  
273 and then fold the clastic dykes through compaction implies that initial injection occurred into  
274 relatively uncompacted host rock (Kane, 2010). The ductile deformation of mudstone and tuff  
275 laminae (tonstein bands; Figs 5B and 6) provides additional support for this interpretation. The  
276 ptygmatic folding of dykes in the SLIS, along with ductile deformation observed in host rocks,  
277 is interpreted to have occurred whilst the host strata remained soft, only partially consolidated  
278 and therefore relatively uncompacted.

279 Injectite margins provide important information concerning wall-rock character, with lobate  
280 structures observed at cusped margins (Figs 5B, 5C, 6A, 7D and 8C) interpreted as forming  
281 through ductile deformation in the host rock by the intruding sand body; these lobate or ‘pod-  
282 like’ features are unlikely to form in more brittle mediums. The presence of cusped margins  
283 therefore suggests injection occurred into soft, unconsolidated and therefore mechanically  
284 weaker sediments. In contrast, smooth margins (Figs 5A and 5D) are interpreted as forming

285 through injection into more brittle host rocks and jagged margins (Fig. 5C) simply reflect  
286 localised erosion along the host rock wall, which could be produced in either softer or more  
287 brittle host rocks.

288 The larger examples of mud-clasts (0.5–5 cm in width) entrained within the dykes were  
289 likely locally sourced, and eroded from the host rock of the injectite during emplacement (*cf.*  
290 Kawakami and Kawamura, 2002; Scott *et al.*, 2009; Ravier *et al.*, 2015). Evidence for localised  
291 erosion of the host rock in the SLIS is presented by jagged margins (Fig. 5C). The larger mud-  
292 clasts had limited transport potential from their sourcing host rock; significant transport  
293 distances in the fracture would otherwise progressively reduce their size through abrasion and  
294 fracturing processes in the flow (*sensu* Smith, 1972). By contrast, the smaller mud-clasts (0.1–  
295 0.5 cm) that form the ‘speckled texture’ (Fig. 5C; which are much smaller than the maximum  
296 dyke aperture), have extended transport potential away from the sourcing host-rock.  
297 Alternatively, the localised enrichment of small mud-clasts through corrasion processes acting  
298 on the host rock wall (*sensu* Scott *et al.*, 2013) is equally possible, although the similar sized  
299 mud-clast populations observed here may indicate at least some component of transport and  
300 sorting away from the host rock source. The possibility for the re-working of mud-clasts, which  
301 were originally part of the depositional sandstone, into the injectite system cannot be  
302 discounted.

303 The syn-sedimentary faulting or reverse displacements (shown in Fig. 5) represent small-  
304 scale examples of classical ‘jack-up’ structures formed during dyke emplacement (e.g. Huuse  
305 *et al.*, 2004; Szarawarska, 2010; Hurst *et al.*, 2016; Hurst and Vigorito, 2017). Collectively,  
306 these small-scale displacements may account for a potentially under-appreciated component of  
307 syn-intrusion deformation throughout an injectite network.

## 308 **CLASTIC SILLS**

### 309 **Description**

310 The clastic sills comprise fine to medium-grained, sub-angular, well-sorted, quartz-rich,  
311 homogeneous sandstones that are concordant with bedding (Figs 7, 8 and 9), with some  
312 contacts inclined by up to 15° relative to bedding. They are encountered in close proximity to  
313 clastic dykes, and are sometimes observed connected to these features (Fig. 6). The sandstones  
314 are variably cemented, with some examples displaying visible porosity and oil-staining (Figs  
315 7A, 7D and 8), whereas others are pervasively cemented (Fig. 7B). Sill thicknesses range

316 between 0.8–70 cm, with a modal thickness of 2 cm. They display a number of margin types,  
317 including stepped (Figs 7A, 7B, 7C and 8A), erosional (Figs 7D, 8D and 8E), flat (Figs 8B and  
318 9) and cusate (Fig. 7D). Sills often coincide (stratally) with light-grey and medium-brown  
319 tuffs (tonstein bands) within the otherwise dark-grey mudstone succession and, in many cases,  
320 intrude entirely within tuffs, often displaying erosional margins (Fig. 10C).

321 Mud-clasts are commonly observed within the sills (Figs 7D, 8 and 9), mostly ranging  
322 between 0.5–5 cm in length; some examples potentially reach >10 cm in length with their edges  
323 extending outside of the core barrel width (e.g. Figs 8A and 9). The mud-clasts generally  
324 display angular to sub-angular edges. They retain much of their original primary lamination,  
325 but often display an elongated or ‘torn’ texture, forming irregular, sometimes rhomboidal  
326 geometries (Figs 7D, 8B, 8C and 8E). In some examples, angular mud-clasts contain internal  
327 injections of sand with cusate margins, which terminate abruptly at the edges of the clasts  
328 (Figs 8A, 8C 8D, 8E and 9B). The mud-clasts are lithologically identical to the surrounding  
329 host rocks, which are composed of hemi-limnic mudstones (as defined in Dodd *et al.*, 2019).

330 Sorting of mud-clasts is present throughout, with the thin sills (1–10 cm thick) containing  
331 small mud-clasts (0.5–2.5 cm wide; Fig. 7D) and the thicker sills (>10 cm thick) containing  
332 larger mud-clasts (2.5–10 cm wide; Figs 9, 9A and 9B), with mud-clast sizes governed by  
333 maximum injectite aperture. A similar relationship has also been observed in sills from the  
334 Karoo Basin in South Africa (Cobain *et al.*, 2015). In some sills in this study mud-clasts are  
335 concentrated near to sill margins (Figs 7D and 9D).

336 There are numerous examples of mud-clast alignment within clastic sills. In some examples  
337 (Fig. 8) mud-clast alignment, mud-clast imbrication and structureless sandstones form a series  
338 of surfaces or ‘sets’ that are inclined relative to sill margins (Figs 8A and 8E), with set  
339 thicknesses approaching 8 cm in places. In these examples, mud-clast concentrations and  
340 maximum clast sizes display variation between individual sets (1–5 in Figs 8C and 8E),  
341 illustrating an element of mud-clasts sorting during deposition.

342 Planar laminations are also observed within sills (Figs 7A, 8A and 8B), highlighted by a  
343 range of aligned, millimetre-scale mud-clasts, tabular sand grains and occasionally instances  
344 of clay or silt-grade material. They are often observed concentrated at, and parallel to sill  
345 margins or slightly inclined, often joining-up to steps at the margins (Figs 8A and 8B). Other  
346 examples of planar laminations are observed in the centre of sills, otherwise composed of

347 structureless sandstone (Fig. 7A). Despite the presence of structuring outlined in these  
348 examples, a high proportion (61%) of the clastic sills are composed of structureless sandstone.

### 349 **Interpretation**

350 The concordant bodies of well-sorted, fine to medium-grained sandstone represent clastic sills  
351 that formed through injection of fluidized sand along bedding planes. The fine to medium-  
352 grain sizes match those of grades known to preferentially-fluidize and re-mobilize (Lowe,  
353 1975). The sills were fed by discordant clastic dyke systems that cross-cut primary bedding  
354 (Fig. 6). There is variability in the style of injection and the resultant deformation of host rocks,  
355 with stepped margins (Figs 7A, 7B and 7C) or flat margins (Fig. 8B) suggestive of brittle  
356 deformation. By contrast, cusped margins indicate softer, more ductile deformation of host  
357 rocks (Fig. 7D). Erosional margins (Figs 7D, 8D and 8E) could form during either brittle or  
358 ductile intrusion events, the character of which would be reflected in the host rock wall  
359 morphology and of the resultant mud-clasts entrained within the flow.

### 360 *Mud-clast geometries and distribution*

361 The angular, irregular geometries of mud-clasts within the clastic sills (Figs 7D, 8 and 9B)  
362 offer some insights into the character of the host rock at the time of intrusion. The irregular  
363 geometries suggest that at least some of the mud-clasts were relatively soft at the time of  
364 erosion and entrainment into the fluidized sand. Elongate (Figs 7D and 8A), irregular and torn  
365 geometries (Fig. 8) likely formed through either shearing/stretching or as a consequence of  
366 squashing/compactional effects during transport (e.g. Jones and Rust, 1983; Pickering *et al.*,  
367 1988). Additionally, their preserved geometries may have been further exaggerated during  
368 compaction and burial. In the opposite scenario where mud-clasts were brittle during transport,  
369 the thin, elongated and irregular forms would likely be broken during transport, making it  
370 difficult to preserve these geometries in the sill. The interpretation of relatively soft mud-clasts  
371 implies that at least some parts of the host rock, from which the mud-clasts were derived, was  
372 relatively soft and therefore only partially consolidated at the time of injection.

373 Furthermore, the examples of internal injectites, entirely contained within a single mud-  
374 clast, typically display cusped margins, with lobate structures (Figs 8A, 8C, 8E and 9B; (some  
375 of which transcend the width of the core; Figs 8A and 9B), whilst the edge of those mud-clasts  
376 appear quite smooth or angular. The presence of cusped margins in these examples is  
377 interpreted to suggest that at least one phase of emplacement of sand occurred within soft,

378 relatively uncompact host rock. However, in order to form the smooth or angular edges of  
379 those mud-clasts, the host-rock would need to be relatively competent at the time of erosion  
380 and entrainment into the fluidized sand. In order to produce these mud-clasts, at least two  
381 injection phases are required. The first phase intruded fluidized sand into soft, uncompact  
382 host rock, forming the internal injectites, and a subsequent phase eroded the more-competent  
383 mud-clasts and deposited them within the clastic sill (Fig. 11). It might be possible to generate  
384 these geometries through a single, protracted injection phase, but this would require an element  
385 of syn-injection consolidation of the host rocks, something that could occur only during a  
386 period of rapid loading and burial.

387 In the two examples that transcend the core width (Figs 8A and 9B) an alternative model is  
388 that they are not clasts at all, but instead intruded host rock, with a network of smaller injectites  
389 connecting two separate sills above and below the mudstone interval. Whilst there is no  
390 unequivocal evidence to suggest or disprove either of these interpretations for these examples,  
391 figure 9C documents a mud-clast that has a very sharp boundary, across which there is an  
392 abrupt and clear grain size difference between the sand matrix of the sill (fine-grained) and the  
393 sand within the mud-clasts (very fine-grained; Fig. 9Bi). This would be extremely difficult to  
394 achieve through a single injection event as it would require a method for sorting of the grains  
395 across that zone. Finally, there is additional evidence for much smaller internally injected mud-  
396 clasts present in the system (Fig. 8E). This mud-clast displays the same internal injections, but  
397 has the advantage of being contained within the width of the core and is surrounded by a sand  
398 matrix; there is no question that this example is a mud-clast suspended in the sill and not  
399 intruded host rock. Together, these factors suggest that internally injected mud-clasts are  
400 present within the SLIS.

#### 401 *Mud-clast alignment, sorting and imbrication*

402 The examples of inclined surfaces or sets of sorted, aligned, often imbricated mud-clasts  
403 (Figs 8 and 9B) are interpreted as having occurred along ripple foresets, forming ripple cross-  
404 lamination within the clastic sill. The foresets show variations in mud-clast concentrations and  
405 sizes (Figs 8C and 8E), indicating an element of sorting occurring during ripple migration  
406 within the injectite system. In these examples, the interpretation of the concordant sandstone  
407 beds as sills, rather than as depositional units, is supported by a clearly-defined stepped upper  
408 margin (Fig. 8A) and upper/lower erosional contacts, with associated feeder dykes and sills

409 (Fig. 8D). In most instances, the ripple cross-lamination forms along the lower margin of the  
410 sill, aggrading towards the centre, suggesting a relationship with the basal contact.

411 Similar inclined sets of mud-clasts and cleaner sandstone have been recognised by other  
412 workers, including: the ‘oversteepened laminae’ identified in figure 4 of Duranti and Hurst  
413 (2004); the differential flow and size differentiation of mud-clasts of Kawakami and Kawamura  
414 (2002); and, crude long-axis clast alignment and irregular low-angle laminae of de Boer et al.  
415 (2007). Furthermore, ripple structures have previously been recorded in injectites, including:  
416 ripple marks’ of Smeyers and Peterson (1971); vertically oriented ‘climbing ripple structures’  
417 in clastic dykes from a glacial setting (Van der Meer *et al.*, 2009); and ‘ripple drift lamination’  
418 observed infilling subglacial hydrofractures (Phillips *et al.*, 2013). The importance of observing  
419 ripple migration within an injectite is that the fluid-sand mix would need to be sufficiently  
420 dilute (and therefore not concentrated) in order to permit ripple-scale bedforms to develop and  
421 migrate within the injectite network. This suggests the fluid-sediment mix during this time was  
422 not concentrated (and not cohesive/laminar flow) and therefore had the potential to be turbulent  
423 in character.

#### 424 *Planar laminations*

425 The planar laminations observed within clastic sills of the SLIS (Figs 7A, 8A and 8B) can  
426 be attributed to two possible mechanisms of formation. Planar laminations within sills have  
427 previously been associated with periods of traction occurring within the fluid-sediment mix in  
428 a clastic sill (Kawakami and Kawamura, 2002; Scott *et al.*, 2009). The alternative method for  
429 generating laminations within a clastic sill is through the shearing of concentrated liquefied  
430 sand, deforming by hydroplastic laminar flow (Lowe, 1976; Allen, 1984; Hurst *et al.*, 2011).  
431 This style of flow may also lead to the generation of flow banding or layering within injectites  
432 (Peterson, 1968; Hillier and Cosgrove, 2002; Kane, 2010), and has also been associated with  
433 consolidation laminae (Archer, 1984). However, taken in isolation it is challenging to attribute  
434 any form of planar lamination to a single flow process as the sedimentary structure can be  
435 formed under a number of conditions.

436 In the SLIS, the planar laminations occur in two main groups: in the middle of sills (Fig.  
437 7A); and at the top of sills (Figs 8A and 8B). In this interpretation, the laminae observed at the  
438 top of sills are attributed to more dilute, potentially turbulent flow, with the laminae forming  
439 near the top during flow deceleration and the onset of tractional processes. This is in contrast  
440 with laminae in the centre of the sills, particularly where they are surrounded by structureless

441 sandstone (Fig. 7A), which are interpreted as forming through the shearing of concentrated  
442 fluid-sediment mixes and therefore associated with laminar flow (Fig. 11).

### 443 **DISTRIBUTION OF INJECTITES**

444 The potential role of injectites to form fluid conduits between otherwise disconnected reservoir  
445 bodies is of particular importance to the hydrocarbon industry (Hurst *et al.*, 2003b; Jonk *et al.*,  
446 2003; Mazzini *et al.*, 2003; Hurst *et al.*, 2011). Therefore, in the case of the hydrocarbon-  
447 bearing Sea Lion, Casper and Beverley fans, it is informative to evaluate the spatial distribution  
448 of the SLIS in relation to these depositional units. As the injectites of the SLIS are only  
449 identifiable in core data, caution must be exercised when considering the distribution of  
450 features in non-cored sections of wells. The injectites are separated into four, stratigraphically-  
451 significant groupings.

452 The stratigraphically lowest grouping of injectites occur above the Bleaker 15 Fan (B15)  
453 and within/above the overlying Sea Lion North Fan (SLN; Figs 2 and 3). The association is  
454 documented in well 14/10-3 (Figs 12 and 13), located to the north of the Sea Lion Field (Fig.  
455 1). This grouping has an apparent dyke-dominance (29 dykes vs. 19 sills), corresponding with  
456 intervals comprising lacustrine mudstone within an otherwise sand-rich succession. The  
457 injectites between SLN and the underlying B15 were formed within the uppermost deposits of  
458 the LC2 sub-unit, whereas the examples within and above SLN are within LC3 sub-unit (Fig.  
459 2 and 3; Richards and Hillier, 2000a).

460 The second grouping are within the overlying Sea Lion Fan (Figs 2, 3 and 4), where the  
461 injectites are observed within the SL15 lobe, in wells 14/10-4, 14/10-6 and 14/10-7 (Fig. 12),  
462 in the northern part of the Sea Lion Field (Fig. 1). To date, injectites are not intersected in SL10  
463 or SL20 (Fig. 12), where the cored intervals are more sand-rich (Fig. 13). The injectites in SL15  
464 have an apparent sill-dominance (3 dykes vs. 14 sills) and are associated with hemi-limnic  
465 mudstone intervals within the fan succession (Fig. 13).

466 The third grouping of injectites is within mudstone-prone successions overlying the Sea  
467 Lion Fan, chiefly above the SL10, in wells 14/10-9Z and 14/15-4Z (Figs 12 and 13). These  
468 wells are located on the western side of the Sea Lion Field (Fig. 1), intersecting the more distal  
469 parts of the Sea Lion Fan (Dodd *et al.*, 2019). These injectites occur in a dense accumulation  
470 between SL10 and the overlying Casper Fan, and like with SL15, have an apparent sill-  
471 dominance (17 dykes vs. 48 sills).



472 The final grouping of injectites are observed surrounding two fan bodies that overly the Sea  
473 Lion Fan: above the Casper Fan in 14/15-4Z; and two examples of dykes above the Beverley  
474 Fan in 14/15-4Z (Figs 2, 3 12 and 13).

475 Injectites are absent in core data from within the SL10 and SL20 lobes of the Sea Lion Fan  
476 in wells 14/10-4, 14/10-5, 14/10-9 and 14/15-4Z (Fig. 12). This may be a function of the core  
477 data representing sand-prone intervals within the wells. The injectites in other fans are more  
478 typically linked to the presence of hemi-limnic mudstones (i.e. in Sea Lion North and SL15;  
479 Fig. 13).

## 480 **DISCUSSION**

### 481 **Sediment flow processes in injectites**

482 The nature of the sedimentary flow processes operating within injectites are still a matter of  
483 debate. Dott (1966) and Taylor (1982) suggested that the flow processes are laminar, while  
484 Duranti (2007) and Hurst *et al.* (2011) suggest an early turbulent flow regime during the initial  
485 phases of hydrofracture propagation, followed by laminar flow during the later stages. The  
486 latter interpretation typically involves a complex combination of processes, leading to a variety  
487 of flow types and resultant deposits (Scott *et al.*, 2009). Furthermore, intrusion events can stop  
488 abruptly when the fluid pressure in fractures drops below that of the local stress oriented  
489 parallel to the opening direction of the fracture, which can lead to grains freezing in place and  
490 injectites that lack sedimentary structure (Jonk, 2010). What is clear is that remobilized,  
491 fluidized sands can have complex transportation mechanisms, leading to a wide variety of  
492 sedimentary structures, or lack thereof, forming within clastic injectite systems.

493 The injectites of the SLIS contain a range of internal structures, the most enigmatic of these  
494 being ripple cross-lamination observed forming at sill margins (Figs 8 and 9B). The structures  
495 are interpreted to have formed through ripple migration within the sill, suggesting periods of  
496 dilute, probably sustained Newtonian fluid flow within the fracture network. A period of  
497 sustained fluid flow is also supported by the presence of imbricated mud-clasts (Fig. 8). The  
498 imbricated mud-clasts can also provide a proxy for flow direction in injectites (Kane, 2010;  
499 Ravier *et al.*, 2015). In the examples provided in figure 8C, the ripple cross-lamination foresets  
500 dip towards the left, whereas the imbricated mud-clasts display opposing dips, towards the  
501 right. These two proxies suggest a consistent flow direction from right to left, but unfortunately  
502 in-situ flow directions could not be obtained as the core dataset is un-oriented. The sorting,

503 deposition along ripple cross-lamination foresets, and imbrication suggests that the mud-clasts  
504 were fully-entrained into a relatively dilute fluid-sand mix; planar laminations developed at the  
505 upper sill contacts (Figs 8A and 8B) may support a flow that underwent sustained periods of  
506 traction (*sensu* Kawakami and Kawamura, 2002; Ravier *et al.*, 2015). Together, these  
507 observations support a period of sustained, relatively dilute, likely turbulent flow occurring  
508 within the fracture network of the SLIS.

509 The generation of ripple cross-lamination would be problematic if an injectite network is  
510 considered as a 'closed system' in which the injectites are not connected to the palaeo-sea floor.  
511 In this scenario, sediment concentrations are more likely to remain high (*sensu* Cobain, *et al.*,  
512 2015), which might imply non-Newtonian fluid and therefore laminar flow behaviour, making  
513 ripple migration, under lower flow regime conditions, difficult to reconcile. However, if a  
514 clastic injectite network is considered as an 'open fracture' (T1 in Fig. 11), where fluids are  
515 free to move towards a palaeo-sea floor, sediment concentration can be diluted (*sensu* Cobain  
516 *et al.*, 2015), flow can be sustained for longer periods of time, and a scenario for ripple  
517 migration is easier to perceive. An initial, period of sustained turbulent flow within the fracture  
518 network is the preferred scenario for the SLIS.

519 This initial period was followed by a subsequent 'closing fracture' phase (T2 in Fig. 11), as  
520 the fluid pressure in the injectite fell below stress perpendicular to the intrusion. During this  
521 time, the reduction of space within the fracture resulted in an increase in grain concentration,  
522 encouraging grain-on-grain interaction that acted to suppress turbulence and resulted in more  
523 laminar flow conditions. Consequently, planar laminations in the centre of injectites  
524 (particularly in sills; Fig. 7A) are interpreted to have formed through the shearing of liquefied  
525 sand under laminar flow conditions during later periods of injection (Lowe, 1976; Allen, 1984;  
526 Hurst *et al.*, 2011).

527 The interpretation of an early period of turbulent flow in the SLIS, followed by a later phase  
528 of laminar flow, confirms previous models of injectite development in other basins (Duranti,  
529 2007; Scott *et al.*, 2009; Hurst *et al.*, 2011). This study therefore represents a case example of  
530 a spectrum of flow processes in operation during injectite emplacement, something that is still  
531 not fully understood (*cf.* Hurst *et al.*, 2011).

## 532 **Style of emplacement**

533 The style of emplacement for clastic injectites is ultimately controlled by the rheological  
534 properties of the host rocks and the driving forces acting on the sediment during deformation  
535 (Toro and Pratt, 2015). In the SLIS, host rocks typically comprise impermeable hemi-limnic  
536 mudstones, interbedded within thinly bedded sandstones forming a heterogeneous succession  
537 (Figs 13 and 14). This lithological heterogeneity can have a significant impact on the variety  
538 of deformation styles observed within the host rocks. This is shown best by a marked  
539 relationship between injectites and the light-grey to brown tuffs (tonsteins) within the mudstone  
540 intervals surrounding the Sea Lion Fan (Fig. 10). The injectites typically show a distinct change  
541 in emplacement style when they encounter these tuffs, which illustrates that the host rock  
542 properties influence, and are influenced by, the intrusion of the injectite systems.

543 The nature of injectite margins and the deformation of the host-strata can provide insights  
544 into the mechanical properties of the host material at the time of injection. In this study, injectite  
545 margins have been grouped into two end members: brittle margins, including stepped, smooth,  
546 and flat; and ductile margins, principally cuscate in form (distribution shown in Figure 13).  
547 Both groups can exhibit erosional characteristics at the margins, which form 'jagged' margins  
548 between the host rock and the sill (Figs 5C, 8D and 8E).

549 Brittle margin types form when fluidized sand intrudes into a relatively competent host rock  
550 (Cobain *et al.*, 2015). In the SLIS the presence of brittle margin types in both dykes (Figs 5A  
551 and 5D) and sills (Figs 7A, 7B, 7C, 8A and 8B) suggests that the host rocks were relatively  
552 competent during at least one period of intrusion. Furthermore, the observation of stepped  
553 margins (Figs 7A, 7B and 8A) is a good indicator for brittle deformation, which are widely  
554 documented, at a variety of different scales, within both clastic (Vétel and Cartwright, 2010;  
555 Cobain *et al.*, 2015) and igneous sills (Thomson and Hutton, 2004; Schofield *et al.*, 2012).

556 Other injectites in the SLIS, which display cuscate margins, particularly those that display  
557 lobate structures (Figs 5B, 5C, 6, 7D and 8C), are interpreted as emplacement through ductile  
558 deformation of relatively soft and probably uncompacted host material. Ptygmatic folding of  
559 the injectites (Figs 5A, 8C and 9C) attributable to post-depositional and post-injection  
560 compaction of both the host rock and the injectites, supports this style of emplacement  
561 (Kuenen, 1968; Hiscott, 1979; Parize *et al.*, 2007; Kane, 2010). Furthermore, a large proportion  
562 of the host rocks contain internal laminations that have been deformed by, or around, clastic  
563 dykes (Figs 5B, 6A, 6B, 9C and 10D). The deformation of laminations within the host rock  
564 may have occurred either during the intrusion event, or much later through differential

565 compaction of mudstones around the more competent injectite structures (Fig. 14), both  
566 scenarios require relatively uncompacted host rocks to form. Finally, mud-clasts within  
567 injectites (Fig. 8) show a range of irregular, elongate and ‘torn/rhomboid’ geometries that  
568 together indicate they were relatively soft or ductile at the time of erosion and entrainment into  
569 the fluidized sand. These geometries are difficult to explain in a scenario where all of the mud-  
570 clasts were brittle or lithified during transport as they would otherwise be broken up within the  
571 flow.

572 There are clearly varying styles of deformation of host rocks formed during the  
573 emplacement of the SLIS. The observed geometries could be explained through a single phase  
574 of injection into host rock that displayed rheological anisotropy. The presence of brittle-ductile  
575 deformation structures and irregularities in injectite geometries has been previously linked to  
576 anisotropy within lithologically heterogeneous, mechanically variable strata (Truswell, 1972;  
577 Toro and Pratt, 2015; 2016). At shallow burial depths, compaction and lithification is likely to  
578 be anisotropic and controlled by lithological variability within a heterogeneous succession,  
579 which leads to a variety of mechanical properties. In this scenario, any intrusive event  
580 associated with injectite emplacement could deform the host sediments in a variety of styles,  
581 including in a ductile manner for the softer sediments, and a brittle manner for the harder, more-  
582 compact lithologies (Hurst *et al.*, 2011).

583 However, the preferred method of attaining the observed mixture of deformation styles in  
584 the SLIS is through multiple phases of emplacement, at shallow burial depths. In this scenario,  
585 there may have been an early injection phase whereby emplacement caused ductile deformation  
586 of uncompacted host rocks, potentially at shallower burial depths. The injectites, and in  
587 particular the dykes, were then ptymatically folded during compaction and lithification.  
588 Subsequently, a second, or a series of injection events occurred in more consolidated  
589 sediments, resulting in brittle fracturing of lithified host rocks during emplacement. Evidence  
590 for multi-phased emplacement for the SLIS includes: variable injectite margin types (Fig. 13);  
591 mud-clasts that contain internal, sometimes ptymatically folded injectites with cusped  
592 margins (Figs 8A, 8C, 8E and 9B); and possibly the observed variability in visible cementation  
593 (i.e. Fig. 7) that may support emplacement by variable fluid types, at different burial depths  
594 and conditions (*sensu* Jonk *et al.*, 2005a); more work is required to address the latter  
595 hypothesis. Having multiple phases of injection that formed the SLIS is consistent with many  
596 other examples of injectite complexes, which typically record several injection episodes, at a  
597 range of burial depths (Duranti *et al.*, 2002; Hurst *et al.*, 2003a).

## 598 **Intrusion mechanisms and depth of emplacement**

599 Injectites are associated with a build-up of fluid overpressures, through a number of processes,  
600 and a subsequent trigger mechanism, which results in the re-mobilization of sand (Hurst *et al.*,  
601 2011 and references therein). The build-up of overpressures is typically associated with fluid  
602 transfer (e.g. formation waters, hydrocarbons, etc.) within the subsurface, which is facilitated  
603 through a number of mechanisms, including disequilibrium compaction during burial (Osborne  
604 and Swarbrick, 1997), injection of fluids into a depositional sandstone, or load-induced over-  
605 pressuring (Hurst *et al.*, 2011). Triggering mechanisms for injection are considered as either  
606 allogenic or autogenic.

607 Allogenic processes include impact or earthquake-related seismicity and are typically more  
608 unusual processes that lead to injectite formation (Hurst *et al.*, 2011 and references therein).  
609 Another, potentially more common allogenic triggering mechanism for injection is the rapid or  
610 accelerated migration of fluids into already over-pressured sandstones. These fluids can  
611 include: formation waters, e.g. bound waters released by the conversion of opal A into opal CT  
612 (Davies *et al.*, 2006; Ungerer *et al.*, 1981; Osborne and Swarbrick, 1997; Mann and Mackenzie,  
613 1990); and oil and gas, which typically migrates at higher pressures from deeper within the  
614 basin (Lonergan *et al.*, 2000; 2002; Jonk *et al.*, 2005b). Given the proximity of the SLIS to the  
615 hydrocarbon-charged reservoirs of the Sea Lion, Casper and Beverley fans (Figs 3, 12 and 14),  
616 and considering the timing of oil generation of the North Falkland Basin petroleum system in  
617 general (as described in Richards and Hillier, 2000a; 2000b), the gradual and then accelerated  
618 migration of hydrocarbons from the deeply buried syn-rift source rocks up and into the shallow  
619 fan sandstones (Fig. 3) offers a plausible primer and triggering mechanism for the SLIS. The  
620 mechanism that permitted multiple phases of overpressure build up and triggering may have  
621 been related to pulsed hydrocarbon generation in deeper parts of the NFB, which lead to  
622 continued re-pressuring of the shallow system after the initial injection event.

623 In this scenario, hydrocarbon generation from source rocks located in the deeply-buried syn-  
624 rift stratigraphy in basin centre (as described in Richards and Hillier, 2000a; 2000b) possibly  
625 led to the build-up of palaeo-overpressures (priming mechanism) through the charging and  
626 migration of hydrocarbon fluids into the shallow, but sealed compartments of Sea Lion, Casper  
627 and Beverley fan sandstones (Figs 3 and 14). At some point, fluid migration may have  
628 accelerated, thereby providing a triggering mechanism necessary for injectite emplacement to

629 occur. At present day, the Sea Lion, Casper and Beverley hydrocarbon reservoirs lack any  
630 evidence for over pressuring (figure 14 of MacAulay, 2015).

631 Finally, autogenic controls, such as instantaneous loading, must not be discounted, as they  
632 are often considered one of the most typical triggering mechanisms (Jonk, 2010; Hurst *et al.*,  
633 2011). Injectites from the Vocontian Basin, Southern France, are interpreted as being formed  
634 within fractures during the emplacement of large volume, sandy flows (Parize and Fries, 2003).  
635 In the SLIS, high-volume sediment gravity flows (high density turbidites; Dodd *et al.*, 2019)  
636 and subsequent instantaneous loading of overlying fan deposits may have generated both  
637 primer and trigger conditions necessary for clastic intrusions to occur. It is possible that a  
638 proportion of the injectites observed within the SLIS are associated with relatively localised,  
639 autogenic processes, particularly those in close vertical proximity to depositional sandstone  
640 bodies.

641 One outcome from the analysis of injectites is to provide estimates for the depth of injectite  
642 emplacement within the subsurface. This is problematical and is often difficult to assess for  
643 many reasons (see Cobain *et al.*, 2015), with only relative depth estimates being possible (i.e.  
644 shallow vs. deep). In the case of the SLIS, the presence of soft, uncompacted host rocks that  
645 display syn-injection ductile deformation of laminae and ptigmatic folding of dykes, suggests  
646 at least one period of intrusion occurred into uncompacted host-rocks, which could only have  
647 undergone limited burial at the time of injection. This suggests at least one phase of  
648 emplacement probably occurred relatively near to the palaeo-seafloor (Fig. 14). A second, or  
649 series of later phases of emplacement may have occurred slightly deeper (but still quite  
650 shallow), with emplacement occurring into more compacted, more brittle host rocks. This is  
651 supported by cusped margins (and therefore shallow injection events) encountered throughout  
652 the SLIS, some of which occur over 60 m of compacted depth (Fig. 13), necessitating more  
653 than one shallow injection event. Finally, the apparent dominance of sill geometries over dykes,  
654 as observed in the SLIS (Fig. 12), has been used previously to suggest relatively shallow burial  
655 of host rocks at the time of injection (Hiscott, 1979; Jolly and Lonergan, 2002; Yang and Kim,  
656 2014; Ravier *et al.*, 2015); although other workers (Vigorito *et al.*, 2008; Vetel and Cartwright,  
657 2010) document sill-dominated intervals of injectite complexes occurring at much greater  
658 depths. Taking these observations into consideration, a general shallow emplacement depth for  
659 the SLIS is concluded in this study.

660 **Spatial relationship between the injectites and the Sea Lion Fan**

661 The distribution of the SLIS around the hydrocarbon-bearing Sea Lion, Beverley and Casper  
662 fans is important to consider as injectites can form fluid-flow conduits in the subsurface.  
663 Injectites are encountered throughout the LC3 sub-unit along the eastern flank of the North  
664 Falkland Basin, with a few observed within the uppermost deposits of the LC2 sub-unit (Figs  
665 2 and 3). All but one cored well (14/10-5) contains evidence of injectites within mudstone  
666 prone successions (Fig. 13); no cored sections of wells were excluded from the dataset due to  
667 a lack of injectites. In general, the injectites tend to occur within the western and northern part  
668 of the Sea Lion Field (Fig. 1). Relatively dense occurrences are typically encountered directly  
669 above individual fans, particularly when there are overlying fan bodies present (injectites  
670 between SL10 and Casper; Figs 12, 13 and 14). The density of the injectites intersected in the  
671 core data suggest they are laterally pervasive features. This implies the fan bodies may be  
672 surrounded by halos of intruded hemi-limnic mudstones, which may have implications in terms  
673 of fluid flow between any isolated bodies of sandstone (over geological timescales).

674 The source of the remobilized sand (often termed the parent sand) is likely to be the adjacent,  
675 under and overlying turbidite fan deposits. This is based on their close spatial association  
676 between a depositional body and dense occurrences of injectites (Figs 1, 12 and 13), which is  
677 potentially documented in core data from well 14/15-4Z (Fig. 9A), although no re-fluidization  
678 features are observed in the underlying parent sandstone in that example. It is often difficult to  
679 accurately determine the exact origin of remobilized sand from core observations alone. Further  
680 studies, such as heavy-mineral assemblage analysis of sandstones intrusions and potential  
681 parent beds (*sensu* Hurst *et al.*, 2017), would be required to better understand these  
682 relationships for the SLIS.

### 683 **Impact on hydrocarbon exploration and reservoir modelling**

684 In the SLIS, a large proportion of the injectites display visible porosity (62% of 143  
685 injectites identified in this study; Figs 5B, 6A, 7A 6B, 8 and 15). Of those examples that display  
686 visible porosity 77% display oil staining (i.e. Fig. 7A). Measured core-plug porosity and  
687 permeability data from both sills and dykes (Fig. 15) display populations between *c.* 17–25%  
688 porosity, with permeabilities of *c.* 10–400 mD. In general, sills have higher porosities and  
689 permeabilities, although a population of dykes exists with *c.* 15–20% porosity and *c.* 10–70 mD  
690 permeability. When considered together, these observations suggest that, at some point in the  
691 past, the SLIS has formed an effective fluid network in the subsurface (Fig. 14).

692 It is also important to consider that a large proportion of the injectites in the SLIS are small,  
693 ranging between 0.8–70 cm in thickness for sills and from 0.25–11.2 cm in width for dykes  
694 (Fig. 15). In many scenarios, these features may be regarded as too small to form significant  
695 fluid conduits between otherwise disconnected reservoir bodies. However, given the relatively  
696 high density of the injectites intersected in the core data (143 injectites identified over 455 m  
697 of core), and considering the limited nature of subsurface core data (*c.* 12 cm wide core vs.  
698 13 km wide fans), they are likely to be laterally and vertically pervasive away from the well  
699 locations. It is possible that, collectively, they could form effective fluid migration routes  
700 between any disconnected sandstone bodies (Fig. 14). Moreover, it is important to consider  
701 that small-scale features are often associated with much larger injection complexes (Ravier *et*  
702 *al.*, 2015). It is quite possible that there will be slightly larger, sub-seismic-scale injectites (*c.*  
703 1–12.5 m wide) in the direct vicinity of the Sea Lion, Casper and Beverley fans. In order to add  
704 to the general understanding of injectites, in particular the sub-seismic-scale features,  
705 quantitative data have been provided (Fig. 15), which could be included within reservoir  
706 models that need to incorporate the potential effects of sub-seismic-scale injectites on reservoir  
707 connectivity during production.

708 The global influence of injectites on fluid flow and hydrocarbon reservoir connectivity is  
709 generally well-known (Thompson, *et al.*, 1999; Lonergan *et al.*, 2000; Hurst *et al.*, 2003b). It  
710 is also well understood that an under appreciation for the presence and extent of clastic  
711 injectites can have both positive and negative consequences for modelling reservoirs for  
712 hydrocarbon production (Purvis *et al.*, 2002). Therefore, an appreciation for potential  
713 heterogeneities provided by sub-seismic-scale injectites, in fine-scale reservoir models, is  
714 important in the accurate characterization of the subsurface around hydrocarbon reservoirs.

## 715 CONCLUSIONS

- 716 1. The 143 injectites of the SLIS contain a suite of sedimentary structures including:  
717 planar lamination, mud-clast sorting, mud-clast imbrication, ripple cross-lamination  
718 and structureless (sandstones).
- 719 2. Injectites are encountered in core data: above the Beaker 15 Fan and within/above the  
720 Sea Lion North Fan; within SL15 of the Sea Lion Fan; in-between SL10 of the Sea Lion  
721 Fan, and the Casper Fan; and above/below the Casper and Beverley fans.



- 722       **3.** The observation of mud-clast imbrication, along with ripple cross-lamination within  
723       sills suggests low concentration, Newtonian fluids potentially flowing in a turbulent  
724       manner within a hydraulically open fracture network. By contrast, the presence of  
725       planar laminations in injectite centres may be related to periods of laminar flow within  
726       a hydraulically-restricted fracture system.
- 727       **4.** In the SLIS, host rocks show evidence for ductile deformation and ptigmatic folding,  
728       suggesting they were relatively uncompacted during injection. However, stepped-  
729       margins indicate elements of brittle deformation during injection. This is attributed to  
730       multi-phased emplacement of injectites at different stages of host-rock lithification, at  
731       shallow burial depths.
- 732       **5.** The injectites of the SLIS display moderate porosity and permeability values, have  
733       visible oil staining, and therefore form potential fluid conduits. These examples  
734       highlight the potential of often overlooked, sub-seismic-scale injectites in forming  
735       effective fluid flow conduits in the subsurface, in general.

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## 999 **Figure Captions**

1000 **Figure 1.)** The location of the Falkland Islands with respect to South America (see inset map; modified  
 1001 after Google Earth, 7.1, 2017), along with the Mesozoic offshore basins, including the Malvinas, South  
 1002 Falkland, Falkland Plateau and the North Falkland basins. The Sea Lion North, Sea Lion, B15, Otter,  
 1003 Casper and Beverley fans were deposited along the eastern flank of the North Falkland Basin (see inset).  
 1004 Nine hydrocarbon exploration and appraisal wells intersect the fans. In six of these wells, 455 m of core  
 1005 data were collected, in which 143 injectites were encountered (injectite density marked by red circles).

1006 **Figure 2.)** The tectono-stratigraphical framework of the early post-rift and middle post-rift sedimentary  
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 1008 Lion (SL20, SL10 and SL15), Otter, Casper and Beverley fans were deposited in LC3, whilst the  
 1009 Bleaker Fan (B15) was deposited in LC2; both units occupying the early post-rift. The sand-rich fan  
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1012 **Figure 3.)** West-east oriented geoseismic section across the Eastern Graben and Eastern Flank of the  
 1013 NFB, near the Sea Lion Fan area (see figure 4 for section location). The ‘transitional’, ‘early post-rift’,  
 1014 ‘middle post-rift’ and ‘late post-rift’ tectono-stratigraphical sequences (as defined in Richards and  
 1015 Hillier, 2000a) represent significant rock units that contain the hydrocarbon system of the NFB. ‘S’  
 1016 symbols in diamond polygons indicate the location of source rocks, whilst ‘R’ symbols in circular  
 1017 polygons indicate known reservoir intervals. The Sea Lion Fan was deposited along the Eastern Flank.  
 1018 Whilst the stratigraphical positions of the ‘B15’, ‘Casper’ and ‘Beverley’ fans have been shown  
 1019 schematically (polygons with dotted outlines), they are not physically present in this section. The  
 1020 relative and stratigraphical distribution of injectites are marked and have been symbolised (not ‘to-  
 1021 scale’).

1022 **Figure 4.)** 3D seismic character across the Sea Lion North, Sea Lion and Otter turbidite fans. Seismic  
 1023 data collected by Polarcus Limited. **A.)** Seismic amplitude extraction map from the Sea Lion North, Sea  
 1024 Lion and Otter fans (number of observed injectites in core data marked by white circles). **B.)** Cross-  
 1025 sectional view through a 3D seismic cube across the fans. The fans are tabular and often composed of  
 1026 a single seismic reflector. Intrusive geobodies are absent from within the seismic data, most likely as a  
 1027 consequence of the scale of the injectites and resolution limitations of the data set (*c.* <12.5 m not  
 1028 resolved). **C.)** A geoseismic interpretation of the fan geobodies and surrounding host mudstones.

1029 **Figure 5.)** Examples of the wide variety of clastic dykes from the SLIS. **A.)** A ptygmatically folded,  
 1030 cemented dyke that displays smooth margins containing a number of 1–2 cm long mud-clasts (14/10-  
 1031 9Z, 2446.81–2447.00 m MDBRT). **B.)** A 3 cm wide dyke, displaying a cusped margin with numerous  
 1032 lobate structures and aligned mud-clasts. A light-grey tuff has been deformed by, or around the intruding

1033 sandstones (14/15-4Z, 2357.21–2357.33 m MDBRT). **C.)** An example of a clastic dyke with a jagged  
 1034 margin and 1–3 mm wide, aligned mud-clasts, forming a ‘speckled texture’ (14/15-4Z, 2449.23–  
 1035 2449.40 m MDBRT). A notable absence of mud-clasts occurs at, and below, the point where the jagged  
 1036 margin is observed, which could be related to a localised eddy in the flow formed as a consequence of  
 1037 interaction/erosion of the host rock wall. **D.)** An example of a clastic dyke, which displays smooth  
 1038 margins and is filled with 1–4 cm long, elongate, aligned mud-clasts. The alignment of mud-clasts is  
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1041 **Figure 6.)** Examples of dyke to sill transitions from the SLIS. **A.)** A 20 cm long, 5 cm wide dyke cutting  
 1042 up stratigraphy and feeding into a sill at the top. The host rocks comprise laminated sandstones and  
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 1044 deformation, indicating they were deformed by, or around, the clastic dyke. The injected sandstones  
 1045 display visible porosity, along with oil staining (14/10-3, 2489.37–2489.58m MDBRT). **B.)** A 45°  
 1046 clastic dyke feeding into a horizontal sill with reverse displacements observed within the host rocks,  
 1047 representing a small-scale ‘jack-up’ structure. Both the clastic dyke and sill display visible porosity,  
 1048 along with oil staining (14/10-3, 2468.10–2468.25 m MDBRT).

1049 **Figure 7.)** A variety of sills and sill-margin types from the SLIS. **A.)** An example of an oil-stained sill,  
 1050 displaying a stepped margin and planar laminations (14/15-4Z, 2453.13–2453.27 m MDBRT). **B.)** An  
 1051 example of a cemented structureless sill, with a stepped upper margin (14/15-4Z, 2445.85–2445.96 m  
 1052 MDBRT). **C.)** An example of a 0.5 cm thick sill, documenting stepped margins at a smaller scale  
 1053 (14/15-4Z, 2449.12–2449.18 m MDBRT). **D.)** A porous sill with erosional margins, where in-situ mud-  
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 1055 MDBRT).

1056 **Figure 8.)** Images of core data (left) and interpreted sections of core (right). **A.)** An example of a 12 cm  
 1057 thick sill, displaying a stepped margin, along with well-developed clast alignment and imbrication near  
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 1059 right of the photo, with some localised mud-clasts that dip in the opposite direction (14/15-4Z, 2474.42–  
 1060 2474.61 m MDBRT). **B.)** An example of a 12 cm thick sill, with well-developed clast-alignment and  
 1061 imbricated mud-clasts that dip to the right of the photo (14/15-4Z, 2475.76-2475.87 m MDBRT). **C.)**  
 1062 A zoomed-in view of the foresets shown in figure 8A. Five different foresets are shown (labelled 1–5),  
 1063 which display variations in mud-clast concentrations and sizes. The large mud-clast at the top has  
 1064 stepped margins and internally contains an injectite with cusped margins, which is ptlygmatically  
 1065 folded. **D.)** An example of a *c.* 10 cm thick sill (14/10-3, 2499.15 m MDBRT), which is fed by (or feeds  
 1066 into) a series of smaller injectites present both above and below the feature. The white box denotes the  
 1067 area shown as a ‘close-up’ in figure 8E. **E.)** A ‘close-up’ view of the basal section of the sill from figure

1068 8D, showing examples of mud-clasts that are: internally injected and irregular in shape; torn or  
1069 rhomboid; imbricated, dipping to the right of the photo; and are sorted into varying sizes and  
1070 concentrations. Like with other examples, ‘foresets’ are visible at the base of the sill (labelled 1–5).

1071 **Figure 9.)** A 35 cm thick sill, overlying a depositional sandstone unit, encountered in-between the  
1072 Casper Fan and the overlying Beverley Fan (see Fig. 12; 14/15-4Z, 2428.60–2431.81 m MDBRT). **A.)**  
1073 The sill displays sharp upper and lower contacts and is composed of well-sorted, fine to medium-grained  
1074 sandstones that display visible porosity, oil-staining and averaged porosity/permeability values 13.8%  
1075 and 33.4 mD, respectively. The underlying depositional sandstone interval may represent the parent  
1076 unit for the overlying injectite system. **B.)** The well-sorted sandstone matrix of the sill shown in figure  
1077 9A, which contains a number of mud-clasts, along with poorly-developed ripple cross-lamination at the  
1078 top. A *c.* 8 cm wide clast, encountered towards the top of the sill displays angular edges and internal  
1079 injectites that display lobate margins and ptygmatic folding. The position of figure Bi is marked by the  
1080 white box. **Bi.)** A ‘close-up’ of the mud-clast boundary documenting a difference in grain size between  
1081 the sandstone matrix of the sill (fine-grained) compared with the sandstone matrix of the internal  
1082 injectite within the mud-clast (very fine-grained). **C.)** An example of intruded host rock from directly  
1083 above the parent sandstone (see figure 9A for the location of this image), documenting a ptygmatically  
1084 folded dyke (note – some drilling-related core breakage in this section).

1085 **Figure 10.)** Examples of injectites intruding into light-grey to medium-brown tuffs (tonsteins). There  
1086 is a clear spatial relationship between the presence of injectites and the tuffs within the core, with the  
1087 injectites often exploiting these mechanically weaker intervals. **A.)** A near vertical dyke that interacts  
1088 with a tuff resulting in the ‘thinning-out’ of siliceous material, along with micro-fracturing (14/10-9Z,  
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1090 9Z, 2444.80–2444.85 m MDBRT). **C.)** A clastic sill intruding completely within a tuff representing a  
1091 zone of weakness (14/10-9Z, 2451.60–2451.82 m MDBRT). **D.)** A clastic dyke arcing down and  
1092 through a tuff, illustrating the preferential relationship between dyke emplacement and the zones of  
1093 weakness (14/10-9Z, 2453.66–2453.79 m MDBRT).

1094 **Figure 11.)** A conceptual model for the infilling of clastic sills with sediment. **A.)** At ‘T1’, the ripple  
1095 cross-lamination is developed during a period when the fracture is open and the sill-dyke systems are  
1096 connected to the palaeo-seafloor. The migration of the ripple bedforms can only take place if the fluid  
1097 concentrations were sufficiently dilute, which might imply an open fracture. Note the erosion of mud-  
1098 clasts from the host rock that contain internal injectites. **B.)** At ‘T2’, the fracture is beginning to close  
1099 or is about to close, with the compression resulting in an increase in sediment concentrations and the  
1100 development of laminar flow. Eventually, this results in the in-situ freezing of typically structureless or  
1101 planar laminated, well-sorted sand, which effectively infills the remaining space in the fracture.

1102 Commonly, this late-stage flow infills the centre of a sill, but theoretically could be found anywhere  
1103 within the fracture.

1104 **Figure 12.)** A broadly north-south oriented (see inset) wireline correlation of cored wells. The vertical  
1105 position in the well and injectite type (sill or dyke shown in red or blue, respectively) are illustrated.  
1106 The injectites are distributed in four groupings: above the Bleaker 15 Fan (B15) and within/above the  
1107 Sea Lion North Fan (SLN); within the Sea Lion 15 lobe (SL15) of the Sea Lion Fan; overlying the Sea  
1108 Lion Fan, chiefly above the Sea Lion 10 lobe (SL10); and above/below the Casper and Beverley Fans.

1109 **Figure 13.)** Sedimentary logs of cored intervals within wells that intersect the Sea Lion North (SLN),  
1110 Bleaker 15 (B15), Sea Lion (SL; 20, 15 and 20), Casper (CA), and Beverley (BEV) fans. The  
1111 sedimentary logs are coloured in terms of facies associations, using the facies model set out in Dodd *et*  
1112 *al.*, 2019. The position of the 143 injectites has been plotted, with dyke or sill geometries recorded as a  
1113 blue and red bar, respectively. Margin types, including: smooth; cusped; stepped; flat; erosional; and  
1114 jagged, have been plotted to demonstrate vertical (and in some respects lateral) distribution of injectite  
1115 morphology.

1116 **Figure 14.)** A conceptual 3D block diagram (schematic), illustrating the distribution, style and  
1117 geometries of injectites observed in the core data through the SLIS, and their relationship with the  
1118 Bleaker 15 (B15), Sea Lion North (SLN), Sea Lion (SL20, SL15 and SL10), Casper, and Beverley fans.  
1119 The injectites of the SLIS have the potential to form fluid conduits between any disconnected reservoir  
1120 intervals, and may have facilitated more effective hydrocarbon migration and charge through the  
1121 succession.

1122 **Figure 15.)** Quantitative data from the 143 injectites of the SLIS, which could be used to populate fine-  
1123 scale reservoir models that need to incorporate the potential effects of sub-seismic-scale injectites. **A.)**  
1124 Scatter plot of core-plug porosity vs. permeability (logarithmic) from both dykes and sills. A linear  
1125 trend of increasing permeability with increasing porosity is displayed. In general, sills display higher  
1126 porosities and permeabilities than dykes. **B.)** Sill thicknesses (cm) within the SLIS. **C.)** Visible porosity  
1127 in the injectites, observable in core data. **D.)** Dyke heights (cm) in core data, with most reaching up to  
1128 25 cm. **E.)** Dyke width (cm) observed in core data. The upper limit of dyke width is limited by the  
1129 diameter of the core data (*c.* 12 cm).

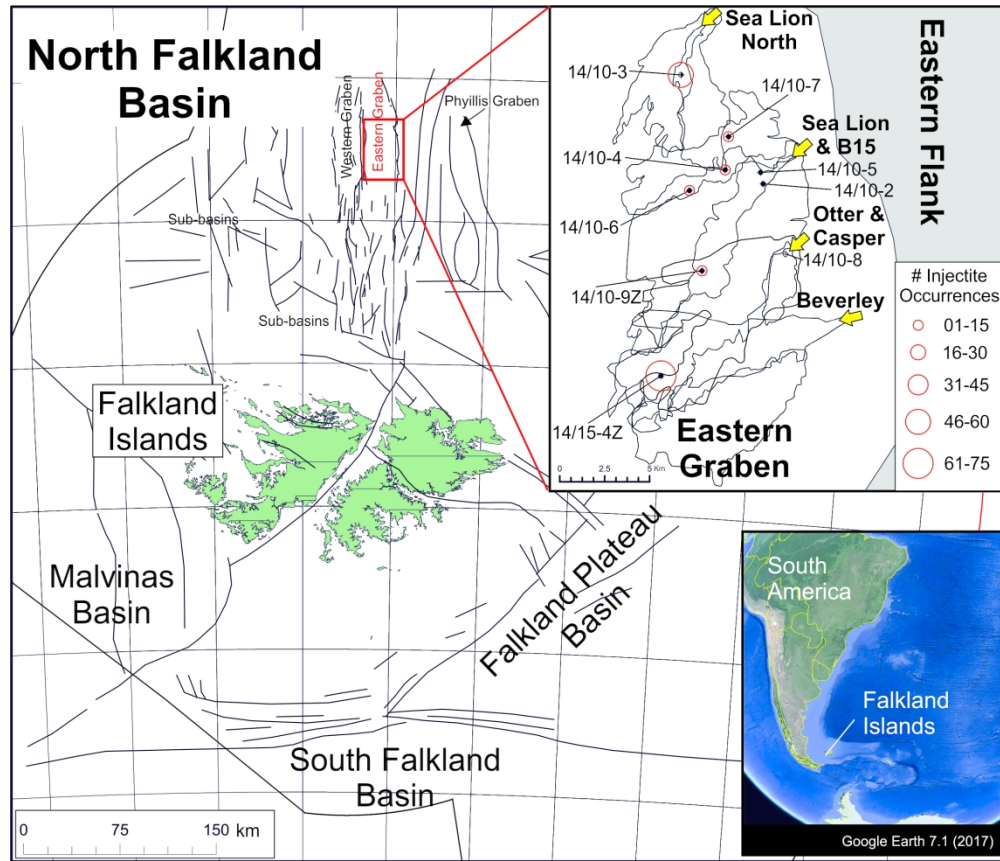


Figure 1

Figure 1.) The location of the Falkland Islands with respect to South America (see inset map; modified after Google Earth, 7.1, 2017), along with the Mesozoic offshore basins, including the Malvinas, South Falkland, Falkland Plateau and the North Falkland basins. The Sea Lion North, Sea Lion, B15, Otter, Casper and Beverley fans were deposited along the eastern flank of the North Falkland Basin (see inset). Nine hydrocarbon exploration and appraisal wells intersect the fans. In six of these wells, 455 m of core data were collected, in which 143 injectites were encountered (injectite density marked by red circles).

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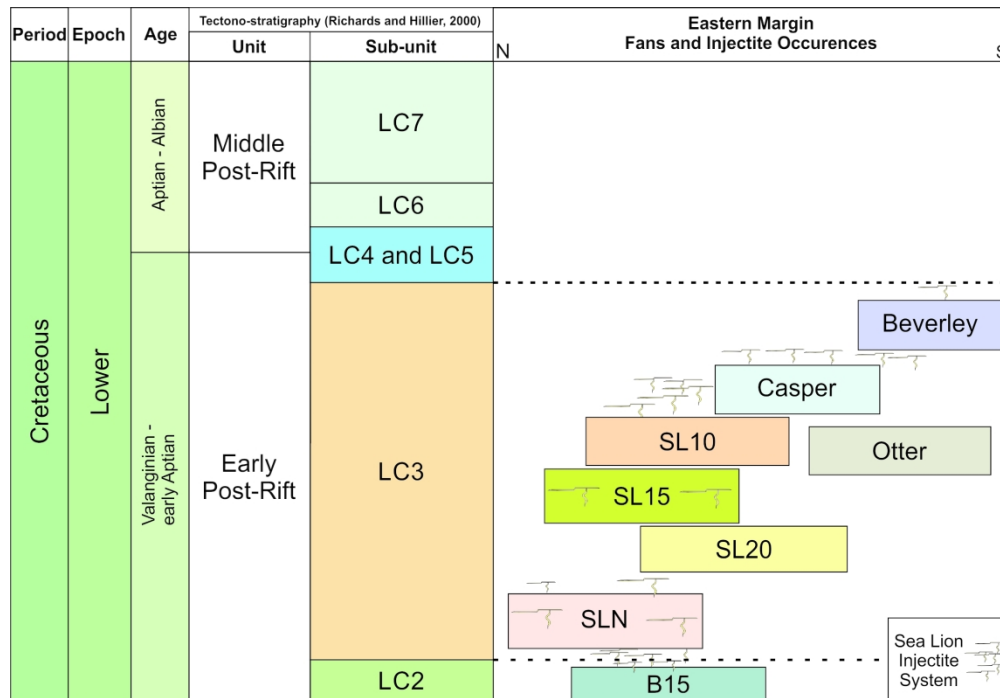


Figure 2

Figure 2.) The tectono-stratigraphical framework of the early post-rift and middle post-rift sedimentary fill of the North Falkland Basin (after Richards and Hillier, 2000a). The Sea Lion North (SLN), Sea Lion (SL20, SL10 and SL15), Otter, Casper and Beverley fans were deposited in LC3, whilst the Bleaker Fan (B15) was deposited in LC2; both units occupying the early post-rift. The sand-rich fan deposits, along with the surrounding hemi-limnic mudstones, were intruded by the Sea Lion Injectite System.

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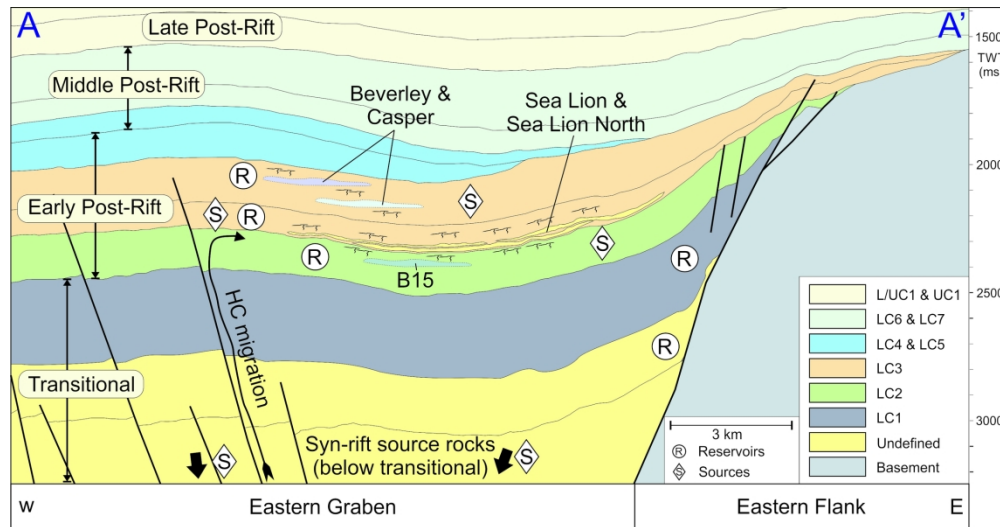


Figure 3

Figure 3.) West-east oriented geoseismic section across the Eastern Graben and Eastern Flank of the NFB, near the Sea Lion Fan area (see figure 4 for section location). The 'transitional', 'early post-rift', 'middle post-rift' and 'late post-rift' tectono-stratigraphical sequences (as defined in Richards and Hillier, 2000a) represent significant rock units that contain the hydrocarbon system of the NFB. 'S' symbols in diamond polygons indicate the location of source rocks, whilst 'R' symbols in circular polygons indicate known reservoir intervals. The Sea Lion Fan was deposited along the Eastern Flank. Whilst the stratigraphical positions of the 'B15', 'Casper' and 'Beverley' fans have been shown schematically (polygons with dotted outlines), they are not physically present in this section. The relative and stratigraphical distribution of injectites are marked and have been symbolised (not 'to-scale').

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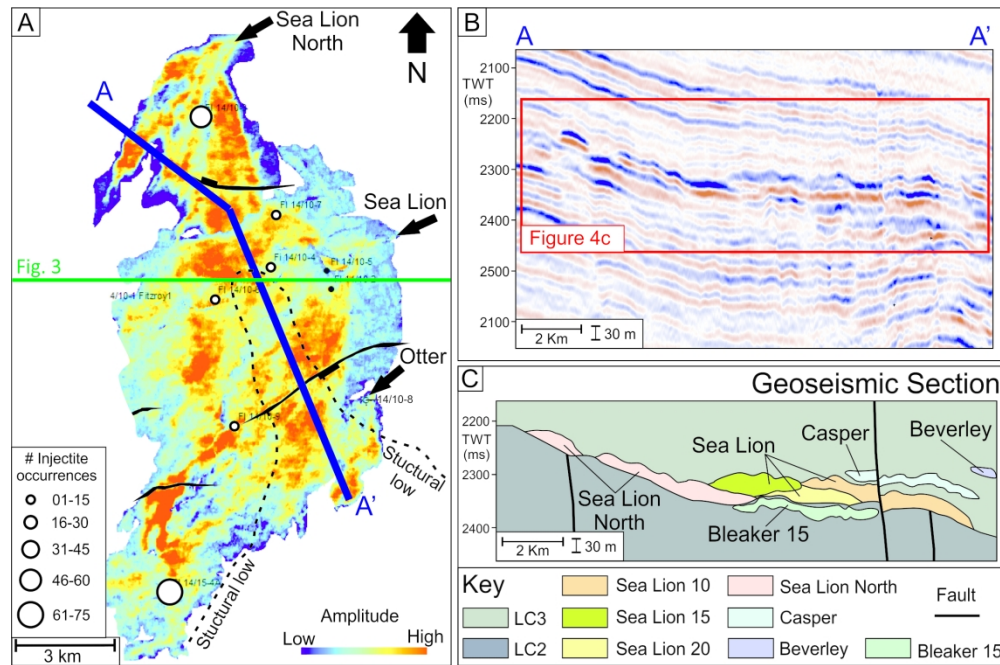


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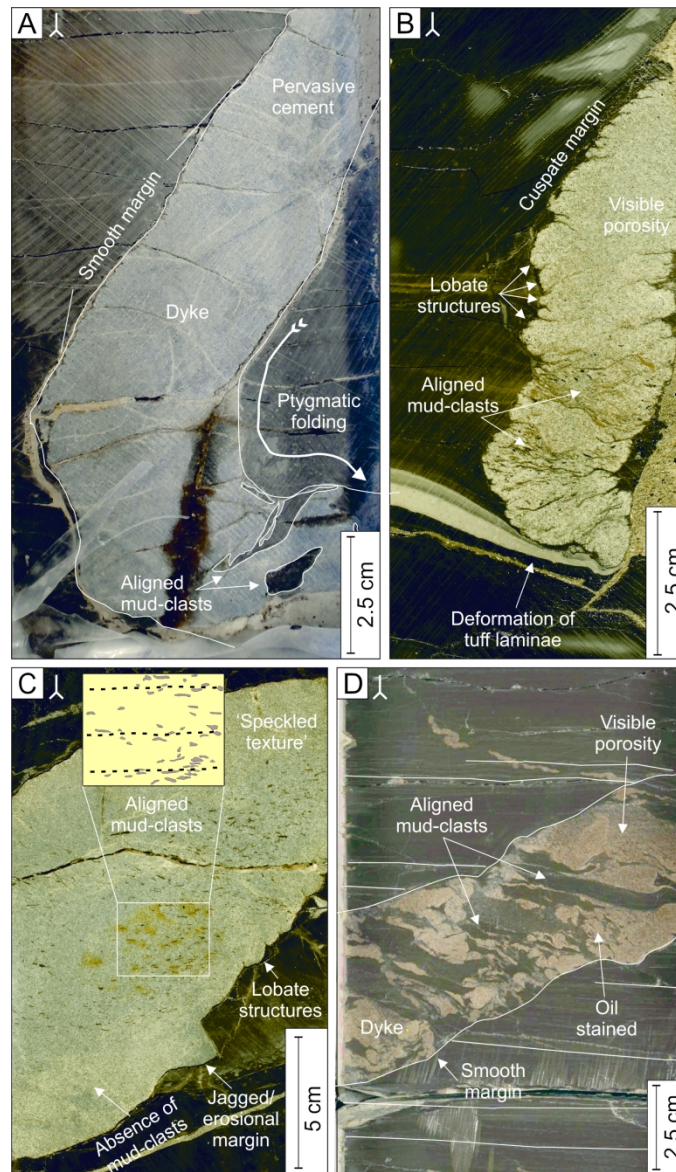


Figure 5

Figure 5.) Examples of the wide variety of clastic dykes from the SLIS. A.) A ptygmatically folded, cemented dyke that displays smooth margins containing a number of 1–2 cm long mud-clasts (14/10-9Z, 2446.81–2447.00 m MDBRT). B.) A 3 cm wide dyke, displaying a cusped margin with numerous lobate structures and aligned mud-clasts. A light-grey tuff has been deformed by, or around the intruding sandstones (14/15-4Z, 2357.21–2357.33 m MDBRT). C.) An example of a clastic dyke with a jagged margin and 1–3 mm wide, aligned mud-clasts, forming a 'speckled texture' (14/15-4Z, 2449.23–2449.40 m MDBRT). A notable absence of mud-clasts occurs at, and below, the point where the jagged margin is observed, which could be related to a localised eddy in the flow formed as a consequence of interaction/erosion of the host rock wall. D.) An example of a clastic dyke, which displays smooth margins and is filled with 1–4 cm long, elongate, aligned mud-clasts. The alignment of mud-clasts is commonly observed within the SLIS, particularly within the thinner examples of dykes (14/10-3, 2496.30–2496.43 m MDBRT).

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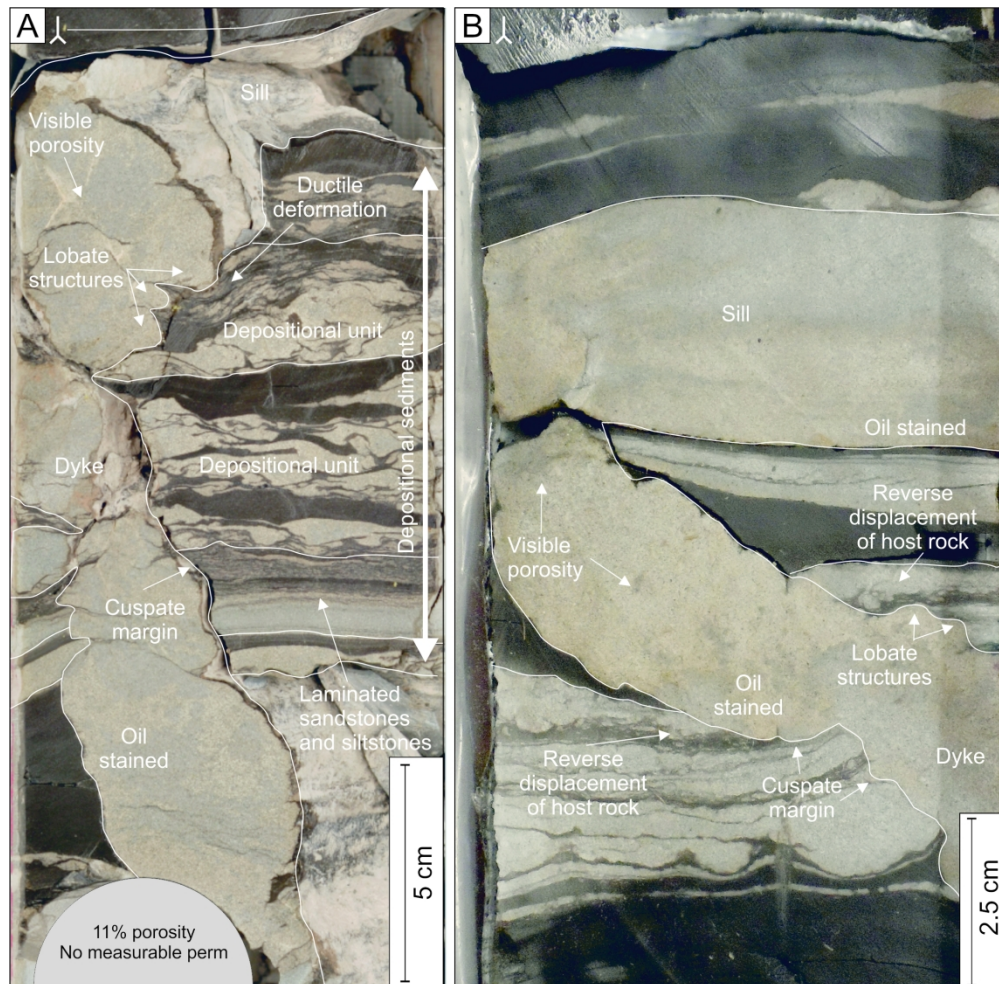


Figure 6

Figure 6.) Examples of dyke to sill transitions from the SLIS. A.) A 20 cm long, 5 cm wide dyke cutting up stratigraphy and feeding into a sill at the top. The host rocks comprise laminated sandstones and siltstones, along with chaotic-textured depositional units. The depositional sediments display ductile deformation, indicating they were deformed by, or around, the clastic dyke. The injected sandstones display visible porosity, along with oil staining (14/10-3, 2489.37–2489.58m MDBRT). B.) A 45° clastic dyke feeding into a horizontal sill with reverse displacements observed within the host rocks, representing a small-scale 'jack-up' structure. Both the clastic dyke and sill display visible porosity, along with oil staining (14/10-3, 2468.10–2468.25 m MDBRT).

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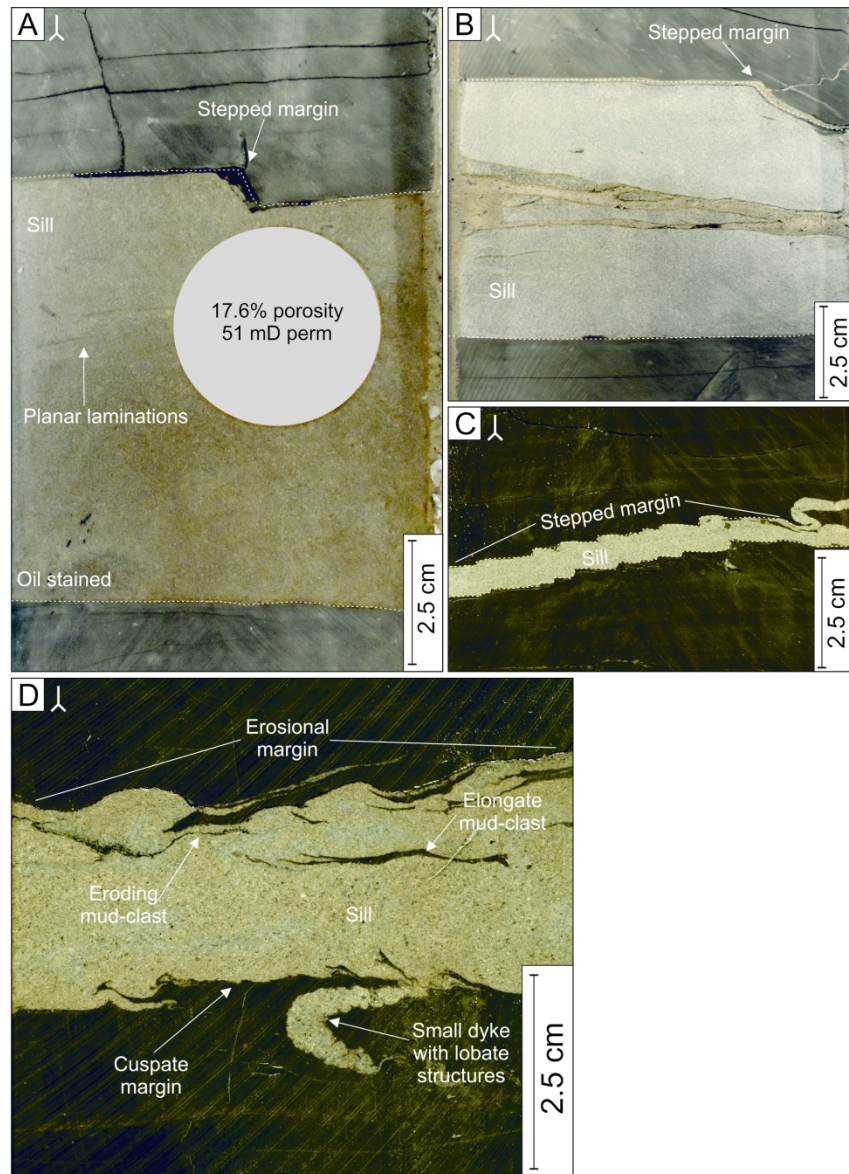


Figure 7

Figure 7.) A variety of sills and sill-margin types from the SLIS. A.) An example of an oil-stained sill, displaying a stepped margin and planar laminations (14/15-4Z, 2453.13–2453.27 m MDBRT). B.) An example of a cemented structureless sill, with a stepped upper margin (14/15-4Z, 2445.85–2445.96 m MDBRT). C.) An example of a 0.5 cm thick sill, documenting stepped margins at a smaller scale (14/15-4Z, 2449.12–2449.18 m MDBRT). D.) A porous sill with erosional margins, where in-situ mud-clasts are preserved in the process of being eroded from the host rock (14/10-9Z, 2455.04–2455.08 m MDBRT).

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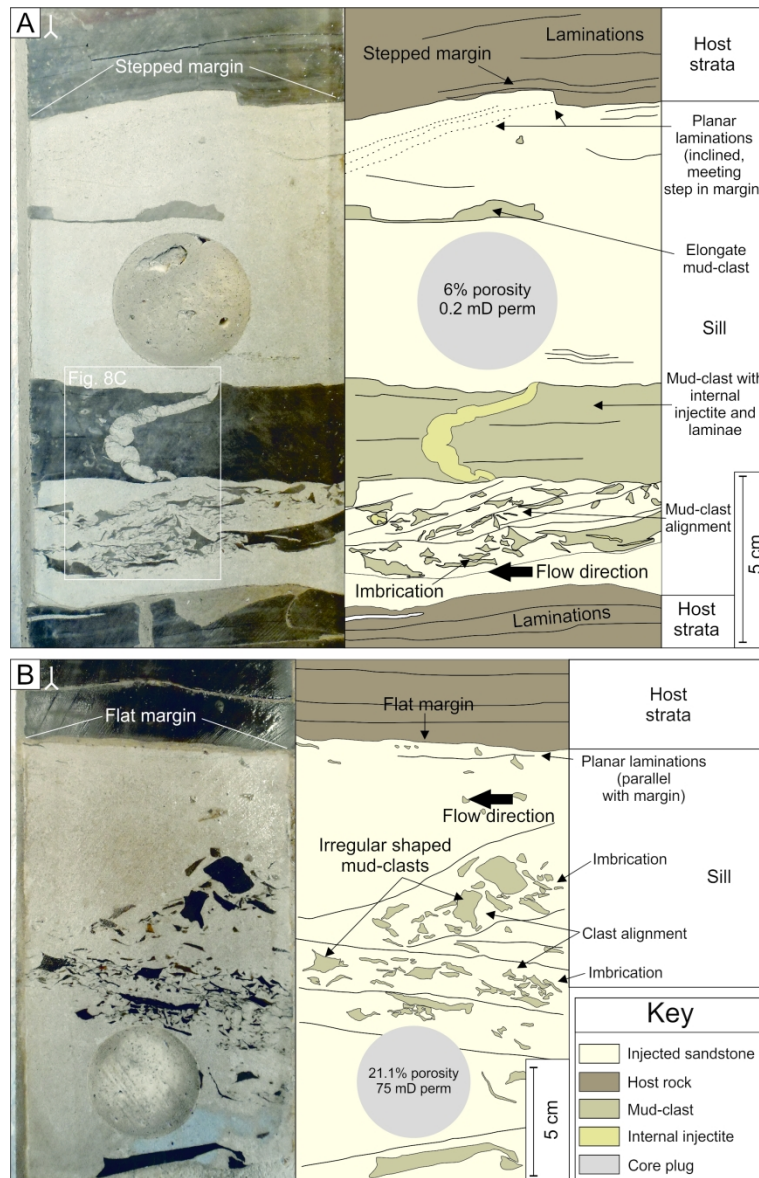


Figure 8A and 8B

Figure 8.) Images of core data (left) and interpreted sections of core (right). A.) An example of a 12 cm thick sill, displaying a stepped margin, along with well-developed clast alignment and imbrication near to the lower margin. A large proportion of the imbricated mud-clasts display a common dip towards the right of the photo, with some localised mud-clasts that dip in the opposite direction (14/15-4Z, 2474.42–2474.61 m MDBRT). B.) An example of a 12 cm thick sill, with well-developed clast-alignment and imbricated mud-clasts that dip to the right of the photo (14/15-4Z, 2475.76–2475.87 m MDBRT).

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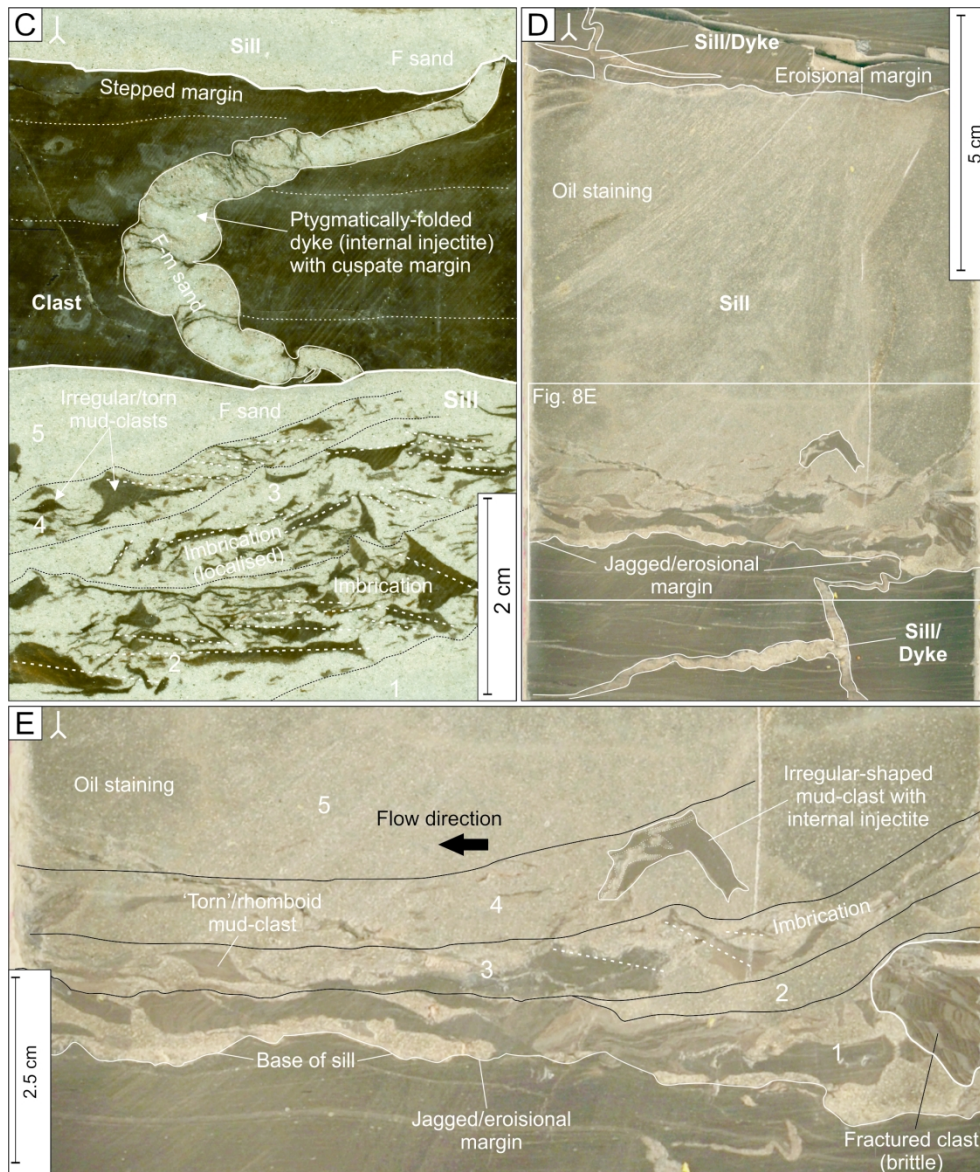


Figure 8C, 8D and 8E

Figure 8. (cntd) C.) A zoomed-in view of the foresets shown in figure 8A. Five different foresets are shown (labelled 1–5), which display variations in mud-clast concentrations and sizes. The large mud-clast at the top has stepped margins and internally contains an injectite with cusped margins, which is ptygmatically folded. D.) An example of a c. 10 cm thick sill (14/10-3, 2499.15 m MDBRT), which is fed by (or feeds into) a series of smaller injectites present both above and below the feature. The white box denotes the area shown as a 'close-up' in figure 8E. E.) A 'close-up' view of the basal section of the sill from figure 8D, showing examples of mud-clasts that are: internally injected and irregular in shape; torn or rhomboid; imbricated, dipping to the right of the photo; and are sorted into varying sizes and concentrations. Like with other examples, 'foresets' are visible at the base of the sill (labelled 1–5).

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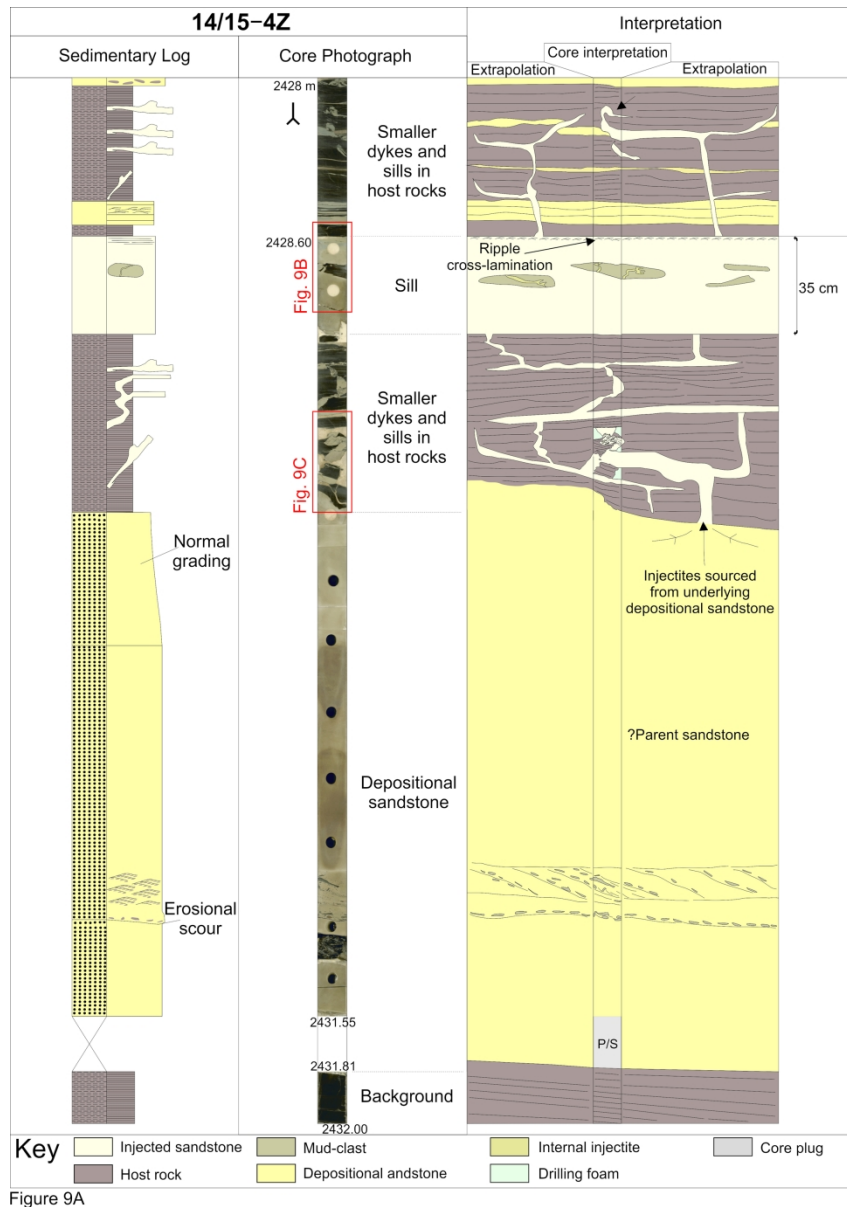


Figure 9.) A 35 cm thick sill, overlying a depositional sandstone unit, encountered in-between the Casper Fan and the overlying Beverley Fan (see Fig. 12; 14/15-4Z, 2428.60–2431.81 m MDBRT). A.) The sill displays sharp upper and lower contacts and is composed of well-sorted, fine to medium-grained sandstones that display visible porosity, oil-staining and averaged porosity/permeability values 13.8% and 33.4 mD, respectively. The underlying depositional sandstone interval may represent the parent unit for the overlying injectite system.

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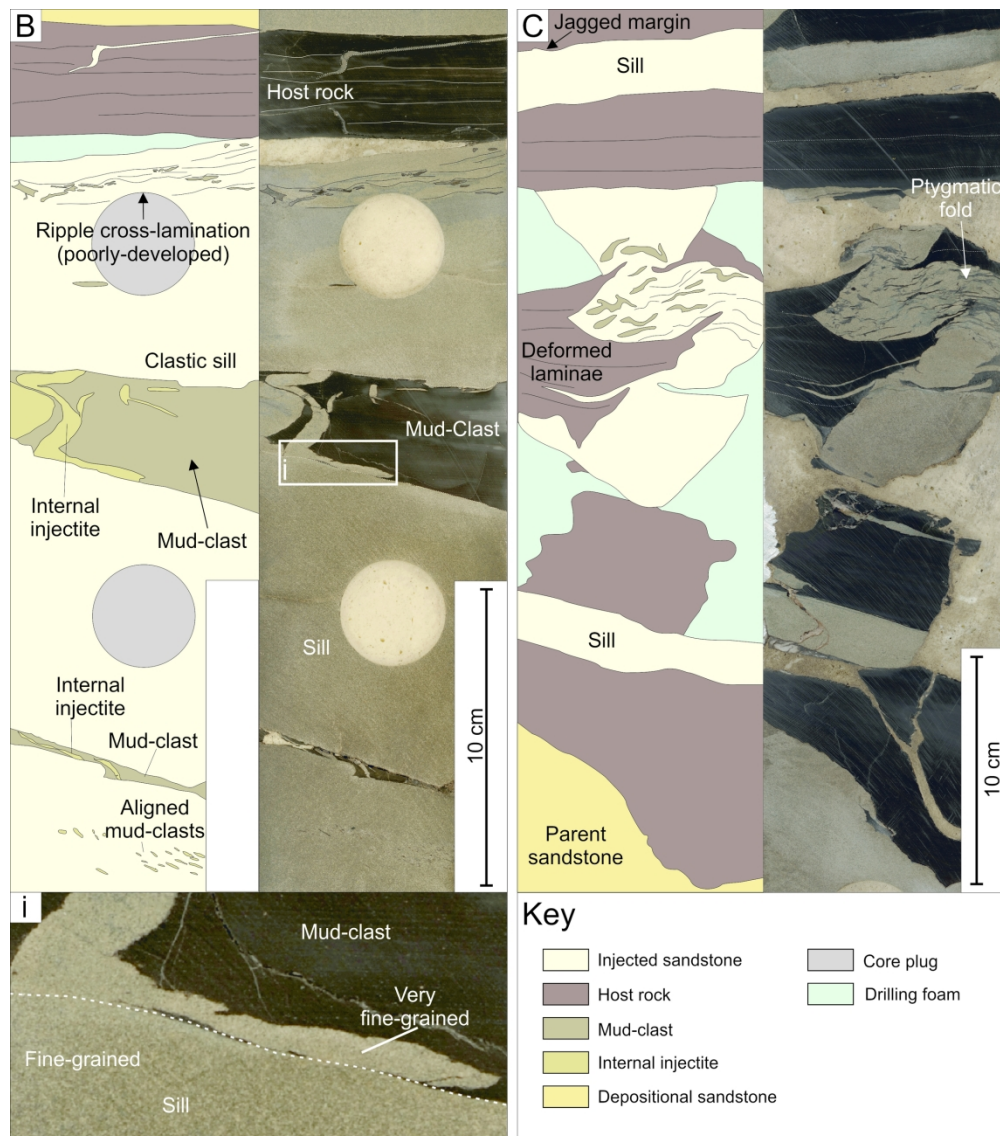


Figure 9B and 9C

Figure 9. (cntd) B.) The well-sorted sandstone matrix of the sill shown in figure 9A, which contains a number of mud-clasts, along with poorly-developed ripple cross-lamination at the top. A c. 8 cm wide clast, encountered towards the top of the sill displays angular edges and internal injectites that display lobate margins and ptygmatic folding. The position of figure Bi is marked by the white box. Bi.) A 'close-up' of the mud-clast boundary documenting a difference in grain size between the sandstone matrix of the sill (fine-grained) compared with the sandstone matrix of the internal injectite within the mud-clast (very fine-grained). C.) An example of intruded host rock from directly above the parent sandstone (see figure 9A for the location of this image), documenting a ptygmatically folded dyke (note – some drilling-related core breakage in this section).

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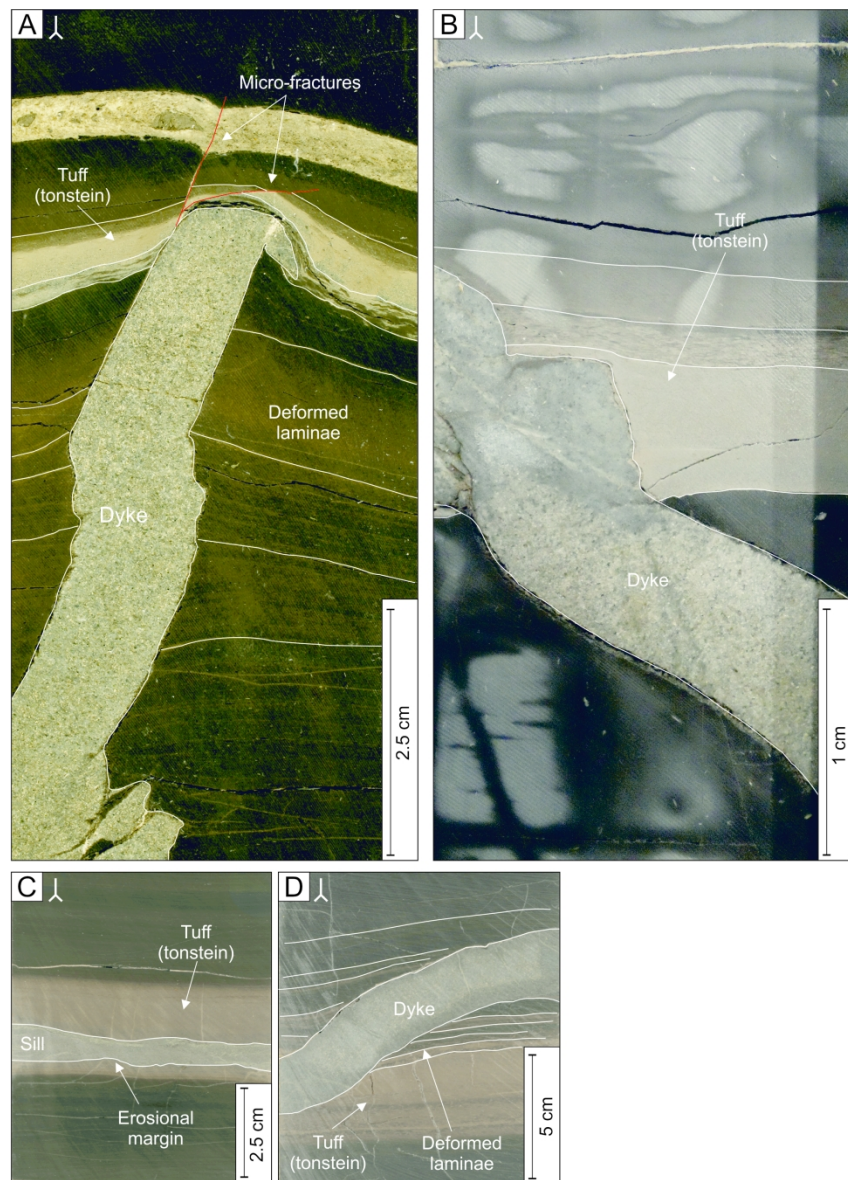


Figure 10

Figure 10.) Examples of injectites intruding into light-grey to medium-brown tuffs (tonsteins). There is a clear spatial relationship between the presence of injectites and the tuffs within the core, with the injectites often exploiting these mechanically weaker intervals. A.) A near vertical dyke that interacts with a tuff resulting in the 'thinning-out' of siliceous material, along with micro-fracturing (14/10-9Z, 2444.79–2444.85 m MDBRT). B.) An example of a clastic dyke cutting into the edge of a tuff (14/10-9Z, 2444.80–2444.85 m MDBRT). C.) A clastic sill intruding completely within a tuff representing a zone of weakness (14/10-9Z, 2451.60–2451.82 m MDBRT). D.) A clastic dyke arcing down and through a tuff, illustrating the preferential relationship between dyke emplacement and the zones of weakness (14/10-9Z, 2453.66–2453.79 m MDBRT).

199x278mm (300 x 300 DPI)

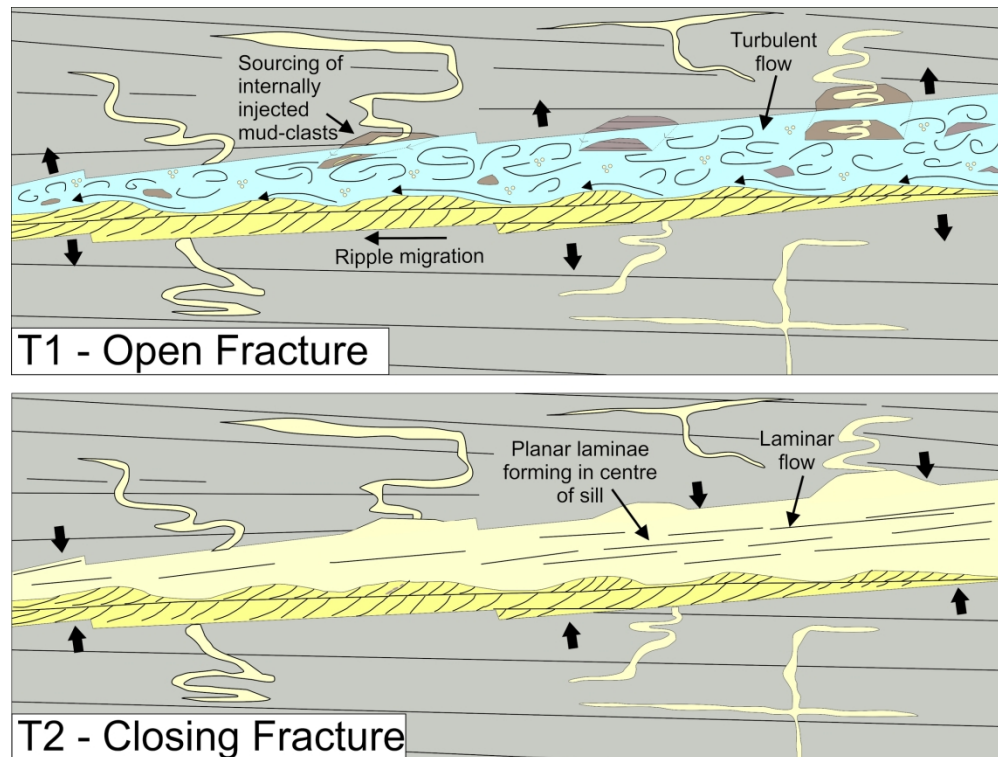


Figure 11

Figure 11.) A conceptual model for the infilling of clastic sills with sediment. A.) At 'T1', the ripple cross-lamination is developed during a period when the fracture is open and the sill-dyke systems are connected to the palaeo-seafloor. The migration of the ripple bedforms can only take place if the fluid concentrations were sufficiently dilute, which might imply an open fracture. Note the erosion of mud-clasts from the host rock that contain internal injectites. B.) At 'T2', the fracture is beginning to close or is about to close, with the compression resulting in an increase in sediment concentrations and the development of laminar flow. Eventually, this results in the in-situ freezing of typically structureless or planar laminated, well-sorted sand, which effectively infills the remaining space in the fracture. Commonly, this late-stage flow infills the centre of a sill, but theoretically could be found anywhere within the fracture.

204x159mm (300 x 300 DPI)

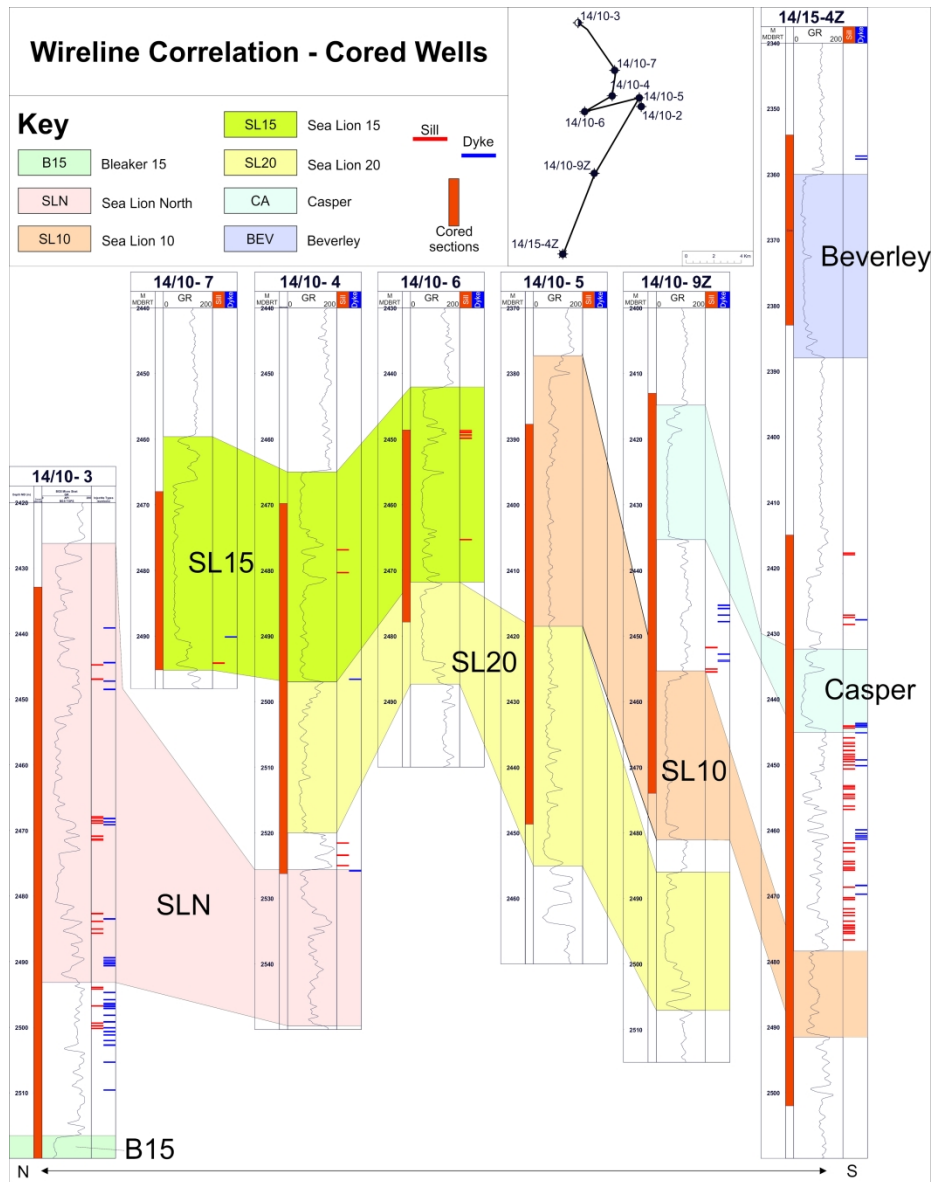


Figure 12

Figure 12.) A broadly north-south oriented (see inset) wireline correlation of cored wells. The vertical position in the well and injectite type (sill or dyke shown in red or blue, respectively) are illustrated. The injectites are distributed in four groupings: above the Bleaker 15 Fan (B15) and within/above the Sea Lion North Fan (SLN); within the Sea Lion 15 lobe (SL15) of the Sea Lion Fan; overlying the Sea Lion Fan, chiefly above the Sea Lion 10 lobe (SL10); and above/below the Casper and Beverley Fans.

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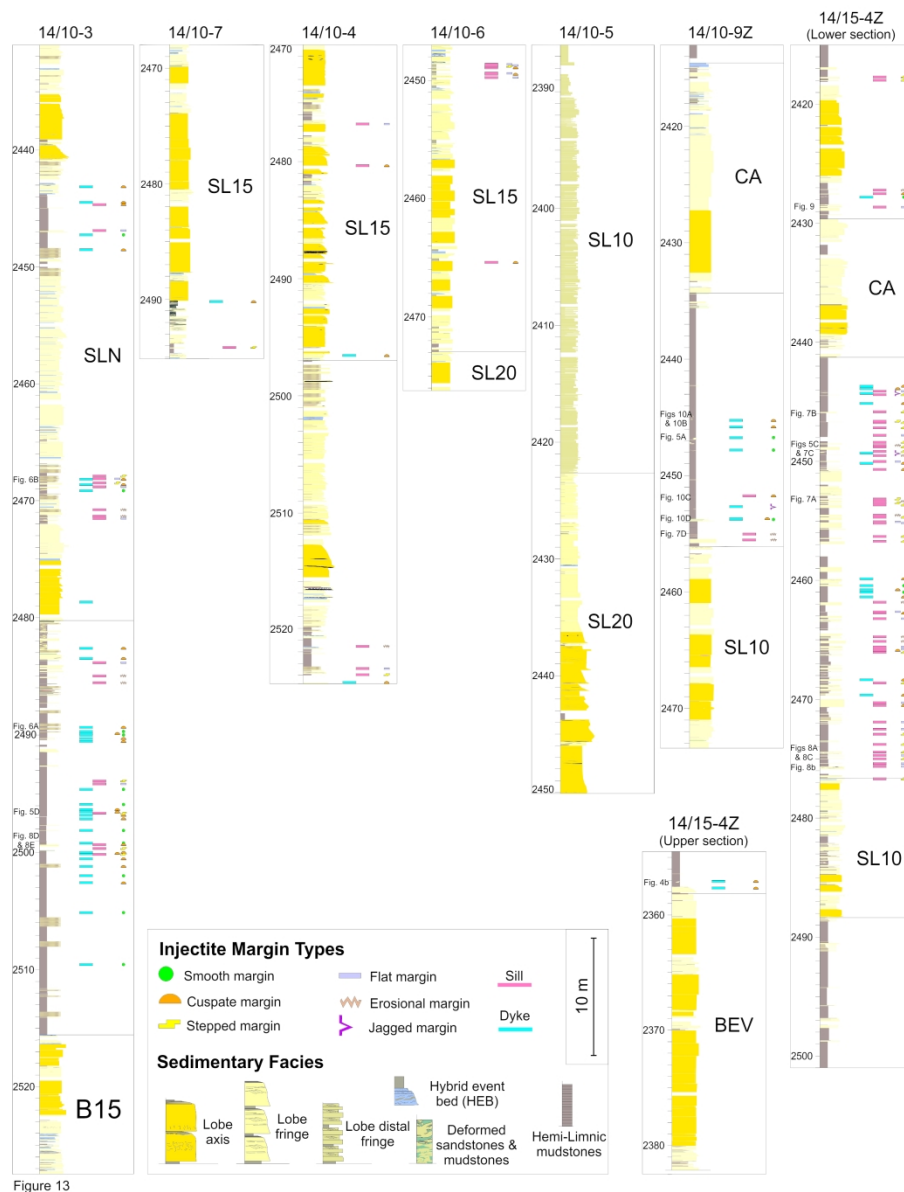


Figure 13

Figure 13.) Sedimentary logs of cored intervals within wells that intersect the Sea Lion North (SLN), Bleaker 15 (B15), Sea Lion (SL; 20, 15 and 20), Casper (CA), and Beverley (BEV) fans. The sedimentary logs are coloured in terms of facies associations, using the facies model set out in Dodd et al., 2019. The position of the 143 injectites has been plotted, with dyke or sill geometries recorded as a blue and red bar, respectively. Margin types, including: smooth; cusate; stepped; flat; erosional; and jagged, have been plotted to demonstrate vertical (and in some respects lateral) distribution of injectite morphology.

286x380mm (300 x 300 DPI)

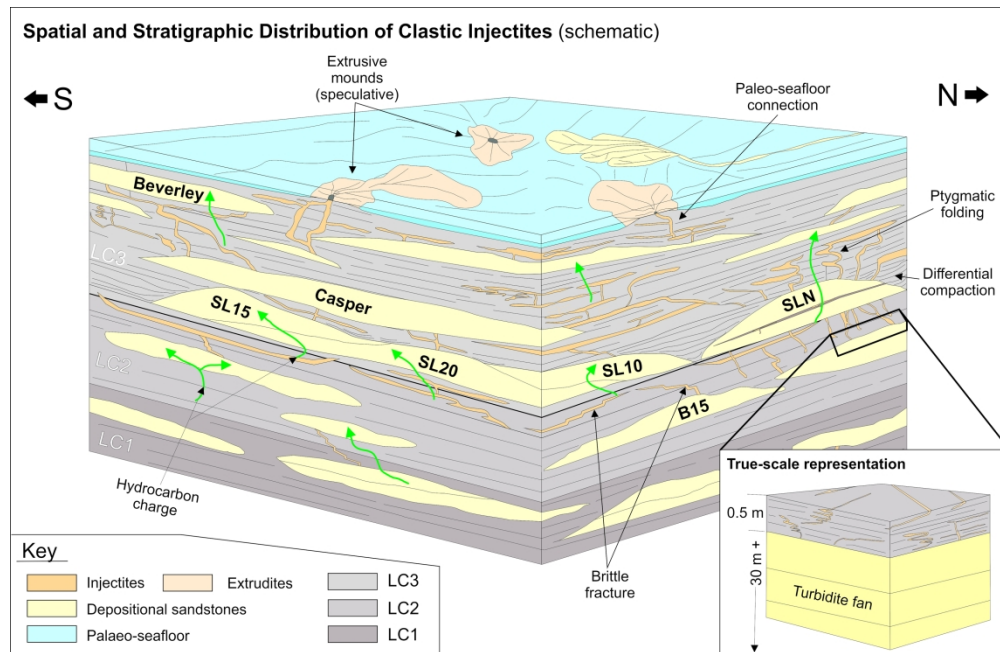


Figure 14

Figure 14.) A conceptual 3D block diagram (schematic), illustrating the distribution, style and geometries of injectites observed in the core data through the SLIS, and their relationship with the Bleaker 15 (B15), Sea Lion North (SLN), Sea Lion (SL20, SL15 and SL10), Casper, and Beverley fans. The injectites of the SLIS have the potential to form fluid conduits between any disconnected reservoir intervals, and may have facilitated more effective hydrocarbon migration and charge through the succession.

288x192mm (300 x 300 DPI)

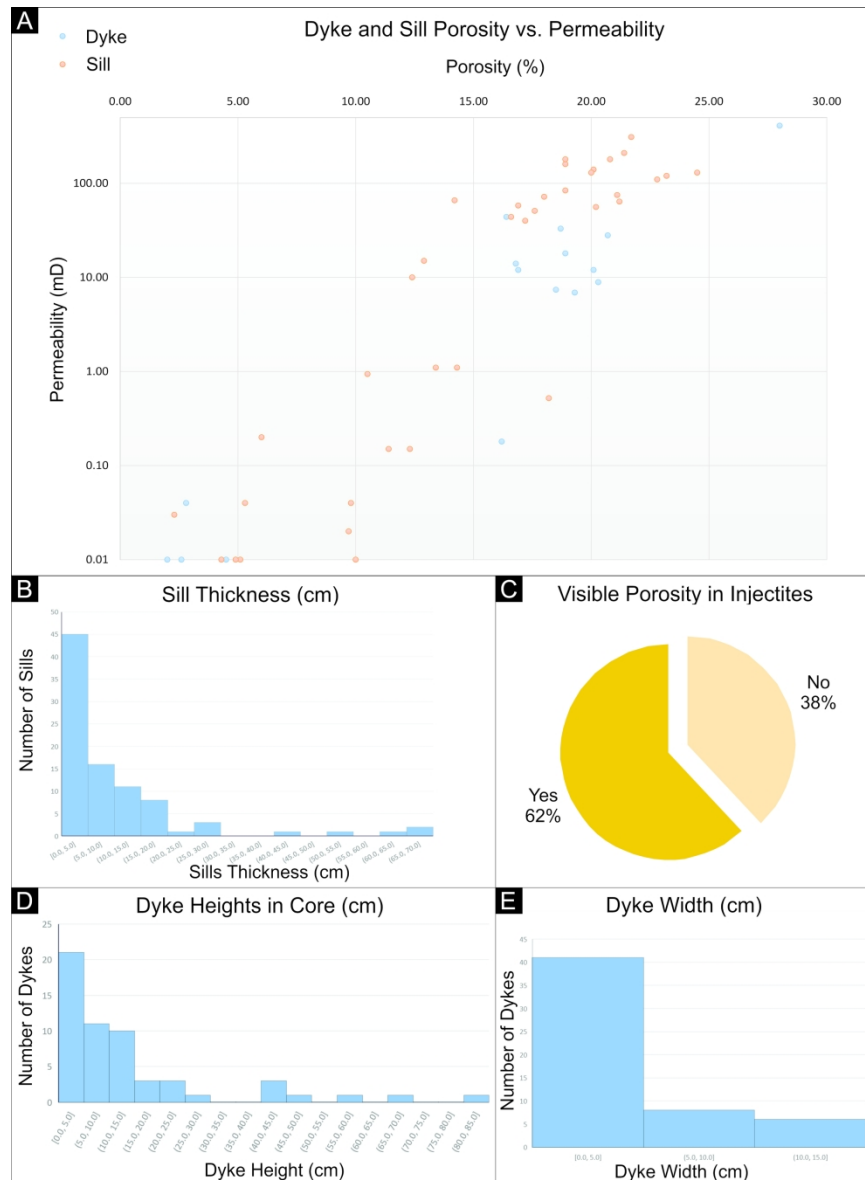


Figure 15

Figure 15.) Quantitative data from the 143 injectites of the SLIS, which could be used to populate fine-scale reservoir models that need to incorporate the potential effects of sub-seismic-scale injectites. A.) Scatter plot of core-plug porosity vs. permeability (logarithmic) from both dykes and sills. A linear trend of increasing permeability with increasing porosity is displayed. In general, sills display higher porosities and permeabilities than dykes. B.) Sill thicknesses (cm) within the SLIS. C.) Visible porosity in the injectites, observable in core data. D.) Dyke heights (cm) in core data, with most reaching up to 25 cm. E.) Dyke width (cm) observed in core data. The upper limit of dyke width is limited by the diameter of the core data (c. 12 cm).

201x280mm (300 x 300 DPI)