

1 **The effect of oil emplacement on quartz cementation in a**
2 **deeply buried sandstone reservoir**

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11 Key words: quartz cementation, quartz cement inhibition, diagenesis, oil charging, reservoir
12 quality

13

14 **Abstract**

15

16 Quartz is an important, porosity-occluding cement in sandstone reservoirs that have
17 been subjected to elevated temperature (>80 °-100 °C) for a substantial period of
18 time. The effect of oil emplacement on quartz cementation in reservoir sandstones is
19 controversial; some studies have concluded that early oil emplacement can inhibit
20 quartz cementation leading to the preservation of porosity, while other studies have
21 concluded that quartz cementation appears largely unaffected by oil emplacement.
22 Here we have studied shallow marine, Upper Jurassic sandstones from Ula Field,
23 Norwegian North Sea, with reservoir temperatures of approximately 150 °C, in order
24 to determine whether oil emplacement had a significant impact on diagenesis with

25 particular attention to quartz cementation. Following sedimentological description of
26 cores, samples above and below the oil-water contact have been collected, adjacent
27 to core analysis plug points. These samples then underwent a series of studies, in-
28 cluding petrographic point counting with a transmitted light microscope, scanning
29 electron microscopy (SEM), backscattered electron microscopy (BSEM), cathodo-
30 luminescence microscopy (SEM-CL), and fluid inclusion studies. These data were
31 integrated with routine core analysis and petrophysical log data. Density and resistiv-
32 ity log data have been used to determine the precise oil saturation of each sample
33 studied. The distributions of all potential controls on porosity and permeability, such
34 as grain size, sorting, matrix clay content, degree of bioturbation, the presence of
35 grain coatings, and dolomite cement, as well as the amount of quartz cement, have
36 been assessed. The presence of primary oil inclusions within quartz cement shows
37 that oil ingress into the Ula reservoir commenced prior to the onset of quartz cemen-
38 tation. Very fine-grained, matrix-rich, bioturbated and microquartz-cemented sand-
39 stones have uniformly low quartz cement contents irrespective of oil saturation. Me-
40 dium-grained, graded, matrix-poor, microquartz-poor sandstones have quartz cement
41 ranging from 1 % to greater than 17 %, associated with core porosities of about 22 %
42 and 7 %, respectively. Higher oil saturations equate to higher porosities and perme-
43 abilities in the medium-grained, graded, matrix-poor, microquartz-poor sandstones,
44 which cannot be explained by any control other than the amount of quartz cement as
45 a function of pore fluid type. Oil emplacement therefore appears to have inhibited
46 quartz cementation at high oil saturations and can be viewed as a significant control
47 on reservoir quality. The significance of this study is that the presence of oil in a
48 sandstone reservoir, at the time that quartz cement was growing, can have a consid-
49 erable impact on reservoir quality. Models that seek to predict quartz cement and

50 reservoir quality in sandstones need to account for the timing of oil emplacement
51 compared to other diagenetic processes.

52

53

54 **Introduction**

55 The aim of this paper is to determine whether oil charge exerted a control on quartz
56 cementation, and consequently preserved porosity, in sandstones from the Upper
57 Jurassic Ula Formation in Ula Field, Norwegian North Sea.

58

59 Understanding whether oil charge has stopped or retarded quartz cementation in the
60 Ula Formation could impact the prediction of porosity and permeability (reservoir
61 quality) distribution, leading to (i) increased accuracy in volumetric reserve
62 estimation (e.g. stock tank oil initially in place: STOIP) and (ii) being able to
63 forecast well performance pre-drill, allowing wells with better delivery to be drilled
64 first. The accurate understanding and prediction of reservoir quality is therefore key
65 in order to obtain predictable well flow-rates throughout the lifetime of a
66 field/reservoir (Sneider, 1990). However, the prediction of reservoir quality is, and
67 will continue to be, a key challenge for petroleum exploration and reservoir
68 development. Defining and reducing risk associated with reservoir quality is
69 especially important in sandstone reservoirs that have been subjected to elevated
70 temperatures (typically taken to be $>100\text{ }^{\circ}\text{C}$) because of quartz, and other deep burial-
71 related, cements, or high effective stress because of compaction (Taylor et al., 2010).

72

73 Quartz is volumetrically the most important cement in deeply buried sandstones
74 (Worden and Morad, 2000). The ability to predict areas within reservoirs, or

75 individual sandstone units, where quartz cement quantity appears to be anomalously
76 low could lead to improved prediction of the distribution of porosity and
77 permeability in reservoirs where quartz cement has been demonstrated to be the main
78 control on reservoir quality. The concept that oil emplacement could inhibit quartz
79 cementation and influence preservation of porosity in sandstone reservoirs became
80 known to many geologists from Johnson's (1920) publication "The cementation
81 process", later developed in a series of papers (Hawkins, 1978; Lowry, 1956;
82 Scholle, 1977; Scholle and Halley, 1985). However, the question of the inhibiting
83 effect of oil on mineral reactions in oil fields remains open and is highly contentious
84 (Sathar et al., 2012; Taylor et al., 2010).

85

86 All diagenetic reactions take place through an aqueous phase, by dissolution,
87 transport and re-precipitation (Worden and Morad, 2000). Hence, for diagenetic
88 reaction to occur there must be aqueous fluid present to dissolve the mineral grains,
89 to transport dissolved material, and to facilitate mineral precipitation. In an oil or gas
90 field, displacement of the aqueous fluid by hydrocarbons within the pore space
91 disrupts the pathway between the reactants and sites of precipitation. As oil
92 saturation increases (i) the residual (irreducible) water becomes isolated within a
93 continuous hydrocarbon phase, (ii) the aqueous pathway becomes tortuous and
94 diffusion rate decreases, or (iii) grain surfaces become coated by oil if the sandstone
95 is mixed- or oil-wet (Barclay and Worden, 2000a). As a consequence, most of those
96 working on diagenesis and sandstone reservoir quality assumed, up to the early-to-
97 mid 1990s, that early oil emplacement halted cementation and preserved porosity.

98

99 Many empirical studies from different basins and from reservoirs of different ages
100 have used, or discussed, the concept that early oil emplacement is a mechanism for
101 porosity preservation in sandstones (Bjørnseth and Gluyas, 1995; Dixon et al., 1989;
102 Emery et al., 1993; England et al., 2003; Gluyas and Cade, 1997; Gluyas et al., 1993;
103 Haszeldine et al., 2003; Higgs et al., 2007; Marchand et al., 2000; Marchand et al.,
104 2001; Marchand et al., 2002; Robinson and Gluyas, 1992; Saigal et al., 1992;
105 Wilkinson and Haszeldine, 2011; Wilkinson et al., 2004; Wilkinson et al., 2006).
106 These studies assumed that replacing formation water with oil simply stopped water-
107 mediated geochemical reactions. However, several other workers have suggested that
108 quartz cementation can continue unhindered even after oil emplacement (Aase and
109 Walderhaug, 2005; Bjørkum and Nadeau, 1998; Ehrenberg, 1990, 1993; Midtbø et
110 al., 2000; Molenaar et al., 2008; Ramm and Bjorlykke, 1994). To explain this rather
111 different interpretation of diagenetic processes, it was assumed that the combined
112 diagenetic processes of dissolution-diffusion-precipitation utilise residual water that
113 clings to grain surfaces, and that this film of water apparently permits mineral
114 diagenesis to continue unhindered.

115

116 Comprehensive overviews of the empirical and theoretical arguments for and against
117 oil emplacement inhibiting quartz cementation (Worden and Morad, 2000; Worden
118 et al., 1998) concluded that the rate of quartz cementation that is synchronous with,
119 or after, oil emplacement in sandstone is probably reduced relative to rates of quartz
120 cementation in the underlying aquifer. These reviews concluded that quartz
121 cementation should be strongly inhibited if (i) the system has mixed wettability or is
122 oil-wet, (ii) the silica is externally supplied, (iii) the rate of diffusion is rate
123 controlling, or (iv) advection is an important part of the transport process. However,

124 even in internally-sourced silica systems with diffusion as the transport control, the
125 overall rate of quartz cementation should be inhibited due to added tortuosity
126 reducing the net rate of diffusion.

127

128 One of the main difficulties in definitively addressing the controversial question of
129 oil inhibition of quartz cement is the large number of potential controls on quartz
130 cementation, such as: (i) primary depositional factors (e.g. facies, grain size, sorting,
131 detrital mineralogy, matrix clay content), (ii) diagenetic factors (e.g. grain coating
132 clay and other minerals, pre-quartz, pore-filling cements, the source of silica), and
133 (iii) pore system characteristics (e.g. wettability and tortuosity). It is also important to
134 consider the oil-filling history of each facies. It is, therefore, possible that previous
135 studies have compared fundamentally different rocks, with different controls on
136 quartz cementation, when attempting to prove or disprove the effect of oil emplace-
137 ment on quartz cementation. In this study, we have taken samples with variable oil
138 and water saturations, as defined by wireline log data. We have been careful to only
139 compare sandstones from the same facies. We have also carefully quantified the
140 presence, type and extent of grain coating materials and taken account of pore-filling
141 cements and only made comparisons between rocks that appear to be as similar as
142 possible (apart from oil saturation). Key questions to be addressed are;

143

- 144 1. What was the timing of oil emplacement relative to quartz cementation in the
145 Ula Formation?
- 146 2. What other potential influences/controls are there on quartz cementation in
147 the Ula Formation?

148 3. Is there a difference in the quartz cement volume as a function of oil saturation
149 for rocks that share similar pre-oil filling characteristics?

150 4. Can any differences in quartz cement volume be attributed to oil emplacement?
151

152

153 **Geological background**

154

155 Ula Field is an offshore oil accumulation located in blocks 7/12 in the southern
156 Norwegian sector of the North Sea (Fig. 1). Ula is located 280 km (149 miles) southwest
157 of Stavanger at the eastern margin of the Central Graben along the Hydra Fault
158 zone (Fig. 1) (Nedkvitne et al., 1993). In addition to Ula Field, three other fields,
159 Gyda, Tambar and Tambar East, combine to make up the Ula-Gyda-Tambar (UGT)
160 area (O'Connor et al., 2011). Ula Field was chosen to undertake this study due to the
161 abundance of available core and supporting downhole data, which not only gives
162 good geographical coverage of the whole field but also gives good stratigraphic
163 coverage through the oil leg, transition zone and water leg.

164

165 Ula Field consists of Mesozoic sediments in an anticlinal structure formed by late
166 Jurassic rifting and subsequent inversion in the Cretaceous and Tertiary (Brown et
167 al., 1992). The main reservoir in the field is the Upper Jurassic Ula Formation (Fig.
168 2) (Bergan et al., 1989; Karlsen et al., 1993; Partington et al., 1993; Underhill, 1998).
169 The Upper Jurassic Mandal Formation is considered to be the source of the petroleum,
170 beginning expulsion from the deeper parts of the Central Graben during the
171 late Cretaceous. Petroleum is still being generated in the UGT area from the Mandal

172 Formation source rock (Taylor et al., 1999). Within the UGT area, the Mandal For-
173 mation also provides the seal for the underlying Jurassic sandstones (Bjørnseth and
174 Gluyas, 1995).

175

176 The Upper Jurassic Ula Formation is a marine sandstone, up to 200m thick, that pro-
177 graded across Haugesund Formation outer-shelf mudstones following a sea level
178 drop in the Kimmeridgian (Harris, 2006). Ula sandstones are typically very fine- to
179 medium-grained, well-sorted, and locally can be glauconitic with some beds rich in
180 shale fragments. Ula Formation sandstones have been described as arkosic (using the
181 McBride, 1963, classification scheme) and were probably sourced from nearby Tri-
182 assic sandstone outcrops (Gluyas, 1997). Much of the Ula Formation has been inter-
183 preted to be intensively burrowed (Baniak et al., 2014; Baniak et al., 2015) and, even
184 where no burrows are evident, physical sedimentary structures can be absent, sug-
185 gesting that the unit has been intensively bioturbated. Facies subdivisions are largely
186 based on grain size and matrix content ; facies 1 is a normally-graded, medium-
187 grained sandstone, with low detrital clay content, facies 2 is a bioturbated fine- to
188 medium-grained sandstone with variable detrital clay content, facies 3 is a very fine
189 to fine-grained sandstone that is intensively bioturbated with a high detrital clay con-
190 tent. Trace fossils are dominated by *Ophiomorpha*, suggesting a high energy, shallow
191 marine (*Skolithos* ichnofacies) origin for the sandstone (Baniak et al., 2015). The Ula
192 Formation contains pervasively carbonate-cemented intervals that have negligible
193 porosity and have been interpreted to result from bedded accumulation of shell debris
194 followed by early diagenetic dissolution and reprecipitation as calcite cement
195 (Gluyas, 1997). Core analysis porosity in the Ula Formation typically lies between 7

196 and 28%. Permeability mostly falls between 650 to 850 mD for the better reservoir
197 units (with extremes between 0.2 and 2800 mD) (Karlsen et al., 1993).

198

199 The Ula Formation in Ula Field underwent more than 2000m of subsidence after the
200 early Oligocene and is slightly overpressured, possibly as a result of the rapid late
201 Tertiary subsidence (Fig. 3) (Harris, 2006; O'Connor et al., 2011). The Ula reservoir
202 has been reported to have a slightly tilted oil-water contact (O'Connor et al., 2011).
203 Reservoir temperature at 3,450 m (11,319 ft) is 143 to 145°C (Home, 1987).

204

205 **Methods and material**

206

207 One hundred and twenty two samples of conventional core plugs from four wells
208 were obtained for petrographic analysis from the BP core store at Reslab laboratories
209 in Stavanger, Norway (Appendix 1). These petrographic samples were taken directly
210 adjacent to plug points for conventional core analysis, thus ensuring that the petro-
211 graphic data tied to the core analysis data. Of the four wells, well 7/12-2 is in the oil
212 leg, and 7/12-A8 is in the water leg, 7/12-3A and 7/12-A13 traverse the oil and water
213 legs. The core sample suite covers the range of present subsurface depths between
214 about 3350 and 3850 m (10,991 and 12,631 ft) TVD, and spans the thickness of the
215 whole reservoir.

216

217 Samples were impregnated with blue resin and then made into polished thin sections.
218 Sandstone modal composition was obtained, in the laboratories at Liverpool Univer-
219 sity, by point counting all thin sections at 400 counts per section. Point counting was
220 performed using a x10 objective but higher power objectives were used where neces-

221 sary, e.g. for finer grained materials and grain coatings. The grid-spacing was se-
222 lected to ensure that the whole thin section was covered. Quartz cement was differen-
223 tiated from quartz grains by virtue of the presence of a trail of inclusions on quartz
224 grain surfaces. Grain sizes and grain coatings were determined for each sample using
225 a Meiji 9000 microscope fitted with an Infinity 1.5 camera. Images were collected
226 and long axes of 100 grains per sample and were measured using Infinity Analyser
227 software, with the images and camera calibrated to standards of known size. Fifty
228 quartz grains per sample were measured in the laboratories at Liverpool University,
229 for the percentage of grain-coating microcrystalline quartz coverage (noting that neg-
230 ligible clay mineral coats were observed) of the freely-exposed grain surfaces, using
231 visual estimates compared to standard grain-coverage images. Only potential sites for
232 quartz cementation (i.e. facing pores, not coated with dead-oil or with clay matrix)
233 that were coated with microcrystalline quartz were measured and expressed as a per-
234 centage of all potential sites for quartz cementation.

235

236 Scanning electron microscope (SEM) examination of all samples was undertaken
237 using a Philips XL 30 SEM with tungsten filament with an accelerating voltage of 20
238 kV, and 8 nA beam current for both secondary electron (SE) and backscattered elec-
239 tron microscopy (B)SEM. The SEM examination was carried out on polished sec-
240 tions and freshly fractured, stub-mounted samples coated with carbon and gold re-
241 spectively. Energy dispersive X-ray analysis (EDAX) provided qualitative composi-
242 tional analysis of clay minerals, carbonate cements and feldspars. Oil-stained sam-
243 ples were soaked in acetone to remove the oil stains which caused problems for the
244 vacuum system in the gold coater. The scanning electron microscope-
245 cathodoluminescence (SEM-CL) images of quartz cemented grains were collected at

246 10 kV by integrating the signals from 16 discrete frames using a slow scanning
247 raster; this took about 8 minutes for each image. The petrographically-defined quartz
248 cement content was compared to the amount of quartz cement discernible from
249 SEM-CL images for three samples, one with high, one with intermediate, and one
250 with a low quartz cement content, to ensure that the point count determination of
251 quartz cement was consistent.

252

253 Doubly polished fluid inclusion wafers for fluid inclusion microthermometric studies
254 were selected to cover all facies from both the water leg and the oil leg and prepared
255 from core samples. An Olympus BX-60 petrographic microscope was used for ther-
256 mometry equipped with a Linkam THMSG 600 heating and cooling stage. This en-
257 abled the measurement of the phase transition temperatures from -180 to 600 °C with
258 an accuracy of between ± 0.1 to ± 1.0 . Observations were made with different magni-
259 fications (objectives 10x, 20x, 50x and 100x). Inclusions were photographed with
260 Digital Camera Olympus DP71 for the purpose of the fast mapping of inclusion loca-
261 tions. Homogenisation temperature measurements were made on each inclusion in
262 each small piece of fluid inclusion wafer and then freezing point depression meas-
263 urements were made on each identified inclusion to prevent modification of the ho-
264 mogenisation temperature (Worden et al., 1995). Fluid inclusion samples were also
265 studied using a mercury UV source to differentiate oil inclusions from aqueous in-
266 clusions with a record being kept of the presence and absence (and relative abun-
267 dance) of petroleum inclusions.

268

269 Petrophysical and conventional core analysis data were made available by BP Nor-
270 way. Porosity and permeability were measured for BP Norway using modern indus-

271 try-standard methods and corrected for confining stress. The permeability data re-
272 ported here were all collected from plugs drilled parallel to bedding (horizontal per-
273 meability). The provided data excluded any anomalous data from fractured plugs.
274 The plugs were collected using industry standard approaches at one every 25 cm
275 (9.84 inches), irrespective of be boundaries to ensure a representative petrophysical
276 dataset. The petrophysical log suites provided for this study were: caliper, bulk den-
277 sity, neutron porosity, sonic transit time, gamma ray, and shallow and deep resistiv-
278 ity. Porosity was calculated for each of the logs using the bulk density log (g/cm^3)
279 and the following relationship:

$$280 \quad \text{fractional porosity} = (\rho_{\text{mbd}} - \rho_{\text{amd}}) / (\rho_{\text{fd}} - \rho_{\text{amd}}) \quad (\text{eq 1})$$

281 Where:

282 ρ_{mbd} = measured bulk density for each sample (from petrophysical logs)

283 ρ_{amd} = average mineral density

284 ρ_{fd} = fluid density

285

286 The average mineral density employed was $2.66 \text{ g}/\text{cm}^3$ (the density of quartz); this
287 average is reasonable since there is a proportion of feldspar with lower density and a
288 proportion of carbonate minerals with higher density. The average fluid density was
289 assumed to be $1.00 \text{ g}/\text{cm}^3$.

290

291 Water saturation was calculated from the petrophysical log data for each 10 cm
292 depth-interval using the Archie equation. Hole conditions were not an issue in the
293 studied section because it did not include poorly-lithified or soluble sections such as
294 mudstones or evaporites. Values of n , a , and m were fixed at 2.0, 0.81 and 2.0, re-
295 spectively, as used by the field operators, following industry standard methods and

296 calibration. Deep induction resistivity log data were used since these give true forma-
297 tion resistivity, unaffected by invasion of the formation by drilling fluids (Asquith
298 and Gibson, 1982). The reported formation water resistivity for Ula Field is 0.025
299 ohm.m (Oxtoby, 1994).

300

301 **Results**

302 *Wireline and core analysis data*

303 The calculated density log porosity values correlate well with the core analysis po-
304 rosity values suggesting that the (wireline) density log porosity values are credible
305 (Fig. 4). The density log-derived porosity and water saturation values for each well
306 are illustrated in Figure 5. The log-derived porosity of the four wells seems to be
307 highest at the shallowest positions with porosity routinely > 20% at the crest of the
308 field but no higher than 10-15 % at the flanks of the field (Fig. 5). The wells included
309 in this study show a wide variation in water saturations; well 7/12-2 has low water
310 saturation, wells 7/12-A13 and 7/12-A08 have high water saturation. Well 7/12-3A
311 has low to intermediate water saturation. The very low porosity and high water satu-
312 ration spikes (e.g. for well 7/12-2) represent pervasively calcite cemented intervals.

313

314 The core analysis data have been split between the three main facies as determined
315 by sedimentological facies description of the core and then further split by the wire-
316 line-calculated water saturations (Fig. 5). Porosity-permeability data for each facies,
317 split by water saturation, are displayed in Figure 6 showing that samples with lowest
318 water saturations, especially from facies 1 and facies 2, have the highest porosity and
319 permeability values.

320

321 ***Facies and detrital minerals***

322 The point count data confirm that the Ula Formation reservoir is an arkosic sandstone
323 (Fig. 7). The wells used in this study and different facies within the core are not dif-
324 ferentiated on the ternary QFL diagram since the data lie in one cluster. The main
325 variations in different facies are in terms of: grain size, clay content and degree of
326 bioturbation. A full listing of petrographic data is given in Appendix 1.

327

328 Facies 1 is medium-grained, moderately well-sorted (0.52 ϕ), with low detrital clay
329 content (mean 4.2 %, Table 1) and no direct sign of bioturbation. Facies 1 tends to be
330 in upward-fining (i.e. graded) beds that are devoid of small-scale sedimentary struc-
331 tures. Point counting results show that the most dominant detrital mineral is
332 monocrystalline quartz (mean 34 %), followed by K-feldspar (mean 11 %) and pla-
333 gioclase (14 %). Polycrystalline quartz and traces of rock fragments are also present
334 in this facies.

335

336 Facies 2 is a fine- to medium-grained sandstone that is moderately- to well-sorted
337 (0.62 ϕ), with a variable detrital clay content ranging from 0.8 to 13.0 % (mean 6.5
338 %) (Table 1). Facies 2 is bioturbated with no remaining primary sedimentary struc-
339 tures due to bioturbation with cm-scale horizontal burrows, identified as *Ophiomor-*
340 *pha* or *Palaeophycus*. The dominant detrital mineral grains in facies 2 are monocrys-
341 talline quartz (mean 28 %), K-feldspar (mean 9 %), plagioclase (mean 15%) and rock
342 fragments (<3 %).

343

344 Facies 3 is a very fine- to fine-grained sandstone that is moderately-sorted (0.83 ϕ)
345 with a high detrital clay content, based on point-count data ranging from 5.7 to 23.2
346 % (mean 11.5 %) (Table 1). Facies 3 is intensively bioturbated with vertical and
347 horizontal burrows identified as *Teichichnus* or *Rhizocorallian*. The dominant detri-
348 tal mineral grains in facies 3 are monocrystalline quartz (mean 27 %), K-feldspar
349 (mean 7 %), and plagioclase (mean 11 %). This facies has localised accumulations of
350 stratigraphically-localized shell fragments and only a small amount of rock frag-
351 ments.

352

353 Detrital clays are present as mm- to cm-sized patches and thin discontinuous layers.
354 Detrital clay is most abundant in the very fine to fine-grained bioturbated facies. Up
355 to 26 % detrital clay is found in the very fine- to fine-grained, highly bioturbated fa-
356 cies and the lowest clay of <1 % are found in the medium-grained graded sandstones
357 devoid of evidence of bioturbation. SEM observations indicate that the detrital clay
358 matrix is dominated by illite and chlorite, confirmed by XRD analyses (trace not il-
359 lustrated in this paper).

360

361 ***Overall paragenesis***

362 A summary paragenetic sequence is presented in Figure 8, with supporting
363 photomicrographs and SEM images in Figures 9, 10, 11 and 13. The sequence is
364 subdivided into ‘early’ and ‘late’ diagenesis. Early diagenetic events took place in
365 depositional pore waters, at relatively shallow depths, with an influence of
366 depositional and influxing meteoric water (Morad et al., 2010), whereas subsequent
367 diagenesis during burial occurred after the main phase of compaction and is
368 characterised by growth at higher temperatures.

369

370 **Early diagenesis**

371 Early diagenesis commenced with admixing and infiltration of detrital clay into the
372 newly deposited sediment, largely due to bioturbation. This resulted in patchy
373 distribution of detrital clays and created locally cleaner pathways that potentially
374 promoted later throughput of diagenetic fluids. This was accompanied by initial
375 compactional porosity-loss, mainly through the reorganisation of grains and
376 mechanical compaction into a stable framework. Framboidal pyrite (Fig. 9a) is
377 associated with detrital clay and precipitated in a reducing environment at relatively
378 shallow depth, during the decay of organic fragments by sulphate-reducing bacteria
379 (Burley & Worden, 2003). Some beds are completely cemented with early diagenetic
380 calcite and have negligible porosity. Dissolution of stratigraphically-restricted shelly
381 carbonate fragments, and the growth of locally pervasive minor non-ferroan calcite
382 within primary pores, occurred during early diagenesis. This led to total occlusion of
383 porosity (see later section on wireline log analysis). Some beds are thus completely
384 cemented with early diagenetic calcite and have negligible porosity. These nodular or
385 bedded early calcite-cemented samples have been excluded from further data
386 analysis (i.e. no point count data for samples with pervasive calcite cement included
387 in Appendix 1) since they do not inform the discussion about the effect of oil
388 emplacement on burial diagenesis (quartz cementation).

389

390 Bacterial sulphate reduction, responsible for framboidal pyrite growth (Fig. 9a), led
391 to acidification, which resulted in minor dissolution of unstable grains and created
392 minor amounts of secondary porosity (Fig. 9b). These minor, partially-dissolved
393 grains were typically replaced by small quantities of patchy, early diagenetic chlorite

394 (Fig. 9c). Chlorite predominantly occurs as minor pore-filling rosettes.
395 Volumetrically, pore-filling chlorite is present in small quantities (typically < 1 %).
396 Chlorite appears to be facies-related with the majority occurring in the very fine- to
397 fine-grained, matrix rich, bioturbated facies 3. Grain-coating chlorite is not present
398 in the studied Ula Formation reservoir sandstones.

399

400 Microcrystalline quartz locally coats grains (Fig. 9d). By reference to evidence from
401 equivalent Upper Jurassic outcrops at Brora, on the NE coast of Scotland, UK,
402 microcrystalline quartz was probably sourced from the dissolution of unstable
403 siliceous bioclasts (e.g. sponge spicules), at shallow burial depths (< 60 °C) (Vagle et
404 al., 1994).

405

406 Further dissolution of feldspar (Fig. 9e) seems to have resulted in the precipitation of
407 a small quantity of early (i.e. pre-compactional) quartz overgrowths, present within
408 quartz-quartz grain contact zones (Figs. 9e-f). Early diagenesis terminated with the
409 end of the main phase of burial-related compaction, which is generally assessed as
410 moderate to strong as evidenced by the prevalence of long and sutured grain
411 contacts.

412

413 **Late diagenesis**

414 Minor feldspar dissolution continued beyond the main phase of compaction, as
415 indicated by locally significant, but volumetrically-minor, secondary pores that have
416 no evidence of compaction. This phase of grain dissolution liberated Al and Si and
417 potentially contributed to the precipitation of the diagenetically-dominant, post-
418 compactional quartz overgrowths (Table 1) and minor quantities of clay minerals

419 (Fig. 9e) (Barclay and Worden, 2000b). The switch from feldspar dissolution to
420 feldspar growth (Worden and Rushton, 1992), required a switch from cation-poor
421 and/or low pH to cation rich and/or moderate pH pore-waters (Fig. 9e). This change
422 also led to local growth of minor quantities of dawsonite (sodium aluminum
423 hydroxycarbonate) within primary pores (Worden, 2006). Minor quantities of late
424 illite precipitated, locally coating quartz overgrowths at this late stage (Fig. 9d).

425

426 Non ferroan and ferroan dolomite cement are present in the Ula Formation (Ula
427 field), with the most volumetrically-important being rhombic ferroan dolomite (Fig.
428 10a). The mean point count volume for total dolomite is ~0.7 %, (Table 1). Ferroan
429 and non-ferroan dolomite are only present in very fine to fine bioturbated sandstones
430 with abundant matrix (facies 3; Table 1). The ferroan dolomite replaces and locally
431 crosscuts quartz cement and so formed after quartz cement. Hydrocarbon influx
432 started after the onset of the main phase of quartz cement growth since residual
433 hydrocarbon is present on quartz cement surfaces (Fig. 10b).

434

435 ***Quartz diagenesis***

436 Both grain-coating microcrystalline quartz and quartz overgrowths are present in the
437 Ula Formation. The Ula sandstones have variable amounts of quartz overgrowth ce-
438 ment ranging from high porosity sandstones with relatively small amounts of quartz
439 cement (i.e. a few percent quartz cement) (Figs. 10a, b and c) to pervasively quartz-
440 cemented samples in which the porosity is almost totally occluded (Figs. 10,d, e and
441 f). Quartz overgrowths are not visibly zoned when studied using SEM-CL (Figs. 10e
442 and f). The euhedral edges of quartz overgrowths are locally stained by dead oil or

443 bitumen (Fig. 10b). However, some low porosity sandstones in the finest grained and
444 most clay-rich facies 3 have little quartz cement due to other pore-filling materials
445 such as abundant pore-filling clay and localised Fe-dolomite (Fig. 10a, Table 1).
446 Quartz overgrowths are euhedral when facing open pores (Figs. 10b, c and e). The
447 boundaries between detrital quartz grains and quartz overgrowths are typically char-
448 acterized by a dust rim composed of fine-grained clay minerals or fluid inclusions
449 (Figs. 10b, c and d). Quartz overgrowths can range in thickness from $< 10 \mu\text{m}$ to $>$
450 $50 \mu\text{m}$. At sites where overgrowths from neighbouring grains interlock, porosity
451 tends to be locally fully occluded. Quartz overgrowths are least abundant in facies
452 type 3 but facies 1 and 2 have highly variable quantities of quartz overgrowths (Ta-
453 ble 1).

454

455 The quartz cement-poor, medium-grained graded samples from low water saturation
456 samples from 7/12-2 notably have relatively clean, largely unmodified (i.e. as-
457 deposited) detrital quartz grain surfaces (Fig. 11). Such grains are marked by a lack
458 of microquartz cement coatings and no more than nascent, patchy and very thin
459 quartz overgrowths (Figs. 11b and d). These clean quartz grains from the oil leg have
460 subtly uneven surfaces that resemble detrital grains from modern environments.

461

462 Quartz cement seems to increase in overall abundance with increasing depth for the
463 medium-grained graded facies 1 (Fig. 12). The same pattern of increasing quartz ce-
464 ment with depth can be discerned for the fine- to medium-grained bioturbated facies
465 2 but there is no pattern for the relatively quartz cement-poor very fine to fine-
466 grained bioturbated facies 3 (Fig. 12)

467

468 Light optics revealed a very fine-grained, colourless mineral coating with low to in-
469 termediate birefringence in some samples (Fig. 13a); SEM observation confirmed
470 that this is microcrystalline quartz (Fig. 13b, Table 1). The quantity of microquartz is
471 greatest in the very fine- to fine-grained bioturbated facies 3, with much less in the
472 fine- to medium-grained and bioturbated facies 2 and medium-grained graded facies
473 1 (Figs. 12 and 14a, Table 1). There is no systematic pattern of microquartz variation
474 with depth of burial (Fig. 12). Some samples have unusually large amounts of micro-
475 quartz, others have low to negligible amounts. The microquartz crystals tend to be <
476 5 μm in size and vary in shape from anhedral (typically rounded) to euhedral. Micro-
477 quartz tends to sit on detrital grain surfaces but locally forms thick irregular coatings
478 that extend into neighbouring pores and pore-filling patches. Microcrystalline quartz
479 cement appears to be dominant only in facies 3 (very fine to fine bioturbated sand-
480 stone with abundant matrix) but it is typically present in small amounts in the coarser
481 facies although one or two samples from the medium-grained graded facies 1 and
482 fine- to medium-grained bioturbated facies 2 contain several percent microquartz.
483 Facies 3 samples tend to have commensurately smaller amounts of quartz cement
484 than the microquartz-poor medium-grained graded facies 1 and fine- to medium-
485 grained bioturbated facies 2 (Table 1; Fig. 14a). As well as point counting micro-
486 quartz, the percentage of detrital quartz grains that are coated with microcrystalline
487 quartz was determined by visually estimating 50 grains per section for a subset of the
488 samples (Fig. 14b). Medium-grained graded facies 1 sandstones have grains that are,
489 on average, about 10 to 20% coated with microquartz and have low overall point
490 counted quantities of microquartz (Figs. 14a and b). Very fine- to fine-grained bio-
491 turbated facies 3 sandstones contain some grains that are approaching 100% grain

492 coating with microquartz. Fine- to medium-grained bioturbated facies 2 sandstones
493 tend to have intermediate degrees of grain coating by microquartz (Fig. 14b).

494

495 ***Fluid inclusion Analysis***

496 Samples for fluid inclusion study were selected from both oil and water legs. Ho-
497 mogenization temperatures were measured for aqueous inclusions and petroleum in-
498 clusions in 12 samples in wells 7/12-2, 7/12-A3, 7/12-5, 7/12-A08, and 7/12-A13 of
499 the Ula Formation. Primary fluid inclusions that fluoresced under UV illumination
500 are present in quartz overgrowths (Fig. 15) showing that some oil was present during
501 the growth of quartz. Non-fluorescent primary aqueous fluid inclusions are also pre-
502 sent in quartz overgrowths. Petroleum inclusions are generally larger in size (Fig.
503 15a-d) and have a higher vapour-liquid ratio than aqueous inclusions and were there-
504 fore easier to work with. Aqueous inclusions range in diameter from 1 to 17 μm . Pe-
505 troleum inclusions range in diameter from 7 to 38 μm . The liquid to vapor ratio for
506 aqueous fluid inclusion was consistently about 8:1 and for petroleum inclusion was
507 about 5:1. All the homogenisation temperatures recorded here are from inclusions
508 within quartz overgrowths or located between detrital quartz grains and their quartz
509 overgrowths. Only homogenization temperatures that were reproducible within (<5
510 $^{\circ}\text{C}$) were recorded. All inclusions homogenised to liquid upon heating. Aqueous in-
511 clusion populations tend to be unimodal between 120 and 174 $^{\circ}\text{C}$ with the lowest re-
512 corded aqueous inclusion homogenization temperature being 103 $^{\circ}\text{C}$. Petroleum in-
513 clusions homogenized between about 80 and 142 $^{\circ}\text{C}$. Pressure corrections were not
514 made to the aqueous inclusion homogenisation temperatures because the formation
515 water was probably saturated with methane at the time of trapping (Hanor, 1980),

516 implying that the measured homogenisation temperatures are representative of the
517 actual trapping temperature for the aqueous inclusions. Homogenisation temperatures
518 of inclusions trapped in quartz are not likely to have been re-equilibrated and so rep-
519 resent the true trapping temperature (Worden et al., 1995). The oil inclusions cannot
520 easily be used to reveal the conditions of trapping since the precise PVT properties of
521 the trapped petroleum are not known.

522

523 Histograms of homogenization temperatures four representative samples are given in
524 Figure 16 and summarized in Table 2. The present-day formation temperature for
525 well 7/12-A3 is 154°C (determined from drill stem testing) which compares favora-
526 bly with the homogenisation temperatures (Fig. 16) although the modal fluid inclu-
527 sion homogenization temperature is lower than the present day temperature.

528

529 **Discussion**

530 *Quartz cementation in the presence of oil*

531 The presence of primary oil inclusions in quartz cement indicates that some oil was
532 present in the reservoir when this authigenic mineral was being precipitated. The
533 very lowest homogenisation temperatures for the aqueous inclusions is 103°C, al-
534 though a more typical minimum homogenisation temperatures for the aqueous inclu-
535 sions is 120°C (Fig. 16) which is somewhat higher than the threshold of 80°C widely
536 assumed to be the temperature above which quartz cement grows (Walderhaug,
537 1996). The oil saturation at the time of the growth of quartz cement, and thus inclu-
538 sion trapping, is not known although it is noteworthy that the fluid inclusion sample
539 with highest oil saturation at the present day (7/12-2, 3403.00m) has the lowest per-

540 centage of quartz cement (Table 2) and was visually estimated to have a relatively
541 great abundance of petroleum inclusions (Fig. 15). Having some oil in the pore net-
542 work clearly does not automatically preclude quartz cementation.

543

544 *Quartz cement modeling in the presence of oil*

545 Simple modeling approaches have been developed to try to link quartz cement abun-
546 dance with burial and thermal histories (Bjørkum et al., 1998; Lander and
547 Walderhaug, 1999; Walderhaug, 1990, 1994a, b, 1996; Walderhaug et al., 2000).
548 These models were calibrated by examining quartz cement quantities in different
549 sandstones from one basin (Norwegian North Sea) and relating these quantities to the
550 burial history of each sandstone reservoir in the calibration dataset. All of these mod-
551 els assumed that quartz cement is internally-derived and that the main control is the
552 rate of quartz precipitation. The timing of quartz cementation in each well was de-
553 rived by using aqueous fluid inclusion temperatures from the sandstones in the cali-
554 bration dataset and the assumption that quartz cementation was continuous from the
555 lowest recorded aqueous inclusion homogenization temperature onwards (despite
556 there being punctuated fluid inclusion records reported) (Walderhaug, 1994a). Geo-
557 metric characteristics were accounted for by examining grain size (and relating this
558 to available surface area) and the fraction of grains that are quartz (as opposed to
559 feldspars, lithics, etc.). The published models were thus calibrated using a number of
560 basic assumptions. Interestingly, the models were also calibrated utilising the funda-
561 mental assumption that emplacement of oil did not inhibit quartz cementation. Since
562 the published models (Walderhaug, 1990, 1994a, b, 1996; Walderhaug et al., 2000)
563 involved the assumption that oil had no effect on quartz cement growth. These mod-

564 els therefore seem to be fundamentally unsuitable for attempting to model any effect
565 of oil emplacement on quartz cementation. However, for medium-grained graded
566 facies 1 and fine- to medium-grained bioturbated facies 2 in the oil leg of Ula oil
567 field, the relative quantity of quartz cement and the elevated porosity look anomalous
568 compared to the quantities found in the water leg (Table 1, Fig. 12). There are a finite
569 number of controls on anomalously high porosity-low quartz cemented sandstones
570 (Bloch et al., 2002); these possible controls will now be examined.

571

572 ***Main controls on porosity-loss above and below the oil-water contact***

573 A comparison of the effects of cementation and compaction using a plot of pore-
574 filling cement versus intergranular volume (also known as a Houseknecht-type plot)
575 (Fig. 17) shows that there is a difference in what process has controlled porosity-loss
576 as a function of position in the oil field. On average, the oil leg samples occupy a
577 central position in the diagram showing a combination of compaction and cementa-
578 tion leading to the final porosity. In contrast the water leg samples sit mainly within
579 the cementation field. The main cement is quartz so that it could be concluded that
580 quartz cement dominates in the high water saturation zone while there has been less
581 cement in the high oil saturation zones (Fig. 17). In contrast, it could also be con-
582 cluded that compaction has been relatively more important than cementation in the
583 oil leg compared to the water leg so that there is a need to compare cement volumes
584 for initially similar samples (same facies) between the oil and water legs.

585

586 ***Grain size, detrital clay and grain-coating microcrystalline quartz and***
587 ***quartz cementation***

588 Grain size is broadly uniform within each facies so that this cannot be invoked as the
589 primary cause of variable amounts of quartz cement in the various facies (Table 1,
590 Appendix 1). Similarly, both fine- to medium-grained bioturbated and medium-
591 grained graded sandstone samples each have approximately consistent quantities of
592 detrital matrix clay, so this, too, can be excluded as a control on quartz cement within
593 each facies (Fig. 12; Table 1). It is noteworthy that very fine to fine bioturbated
594 facies 3 has a far higher quantity of matrix clay than medium and coarse facies 1 and
595 2. However, for the water leg samples from the three facies, there is a well-
596 developed, inverse correlation between the amount of detrital clay and the amount of
597 quartz cement (Table 1). This suggests that the more argillaceous-rich, finer-grained,
598 heavily bioturbated samples have experienced inhibition of quartz cement compared
599 to the cleaner medium- and coarse-grained sandstones. Ferroan dolomite is not a
600 major mineral cement but it too correlates with primary facies and detrital clay
601 content possibly (Table 1).

602

603 Microquartz is an abundant, and pervasively grain-coating, cement found on detrital
604 quartz grains in the very fine- to fine-grained bioturbated facies 3 (Fig. 14). Quartz
605 cementation appears to have been inhibited by microquartz coats irrespective of pore
606 fluid type (Fig. 12; Table 1). This effect has been reported previously (Aase et al.,
607 1996; French and Worden, 2013; French et al., 2010; French et al., 2012; Hendry and
608 Trewin, 1995; Ramm et al., 1997; Weibel et al., 2010; Worden et al., 2012). It is
609 significant that a small subset of fine- to medium-grained bioturbated facies 2
610 samples contain measurable microquartz (Fig. 14a). These samples have

611 commensurately reduced amounts of quartz cement and elevated porosity. For
612 example, samples of fine- to medium-grained bioturbated facies 2 in well 7/12-3A at
613 3,559-3,566 m (11,677-11,699 ft) TVDss contain a few percent microquartz (Fig. 12)
614 and have anomalously elevated porosity as a consequence of the inhibition of quartz
615 cement (Figs. 5 and 12).

616

617 When grain-coating microquartz percentage, and percentage of surface area of grain-
618 coating by microquartz, are plotted against quartz cement (Fig. 14a), it is apparent
619 that samples from medium-grained graded facies 1 (and fine- to medium-grained
620 bioturbated facies 2) show a large range of quartz cement volumes irrespective of the
621 amount of microquartz. Although microquartz exerts a control on the development of
622 quartz overgrowths, it is not particularly abundant in medium-grained graded facies 1
623 or fine- to medium-grained bioturbated facies 2 and it cannot explain the full range
624 of abundance of quartz cement. This suggests that there is an additional control, other
625 than microquartz, that has determined the amount of quartz cement in facies 1 and 2.

626

627 Since grain-coating microquartz is only observed in large amounts in very fine- to
628 fine-grained bioturbated facies 3, it seems likely that this is the only facies in which
629 there was an abundant potential source for the microquartz. Microquartz in Upper
630 Jurassic sandstones from the North Sea is typically attributed to detrital sponge
631 spicules (Aase et al., 1996; Vagle et al., 1994). Based on the literature-based
632 interpretation that the microquartz was sourced from replaced sponge spicule
633 fragments, it can thus be inferred that detrital fragments of sponge spicules were
634 preferentially concentrated in the finest-grained sand fraction. We here speculate that
635 the grading of the silica bioclasts into the finest sand fraction may be a consequence

636 of their fragility and consequent attritional diminution during transport from their
637 original location on the marine shelf. While these silica bioclasts have successfully
638 led to the inhibition of quartz cement (good for reservoir quality), they are found in
639 the finest sandstones (facies 3) that also contain abundant matrix clay so that the
640 reservoir quality has been detrimentally controlled by other factors.

641

642 ***Quantity of quartz cement above and below the oil-water contact for***
643 ***rocks of the same pre-oil filling characteristics?***

644 The characteristics of the three different primary facies above and below the oil-
645 water contact (and in the transition zone) are summarized in Table 1. The three facies
646 have been defined by grain size, matrix clay content and sedimentary structures (in-
647 cluding grading and degree of bioturbation) and so have self-consistent grain size
648 and sorting characteristics and detrital mineralogy (Fig. 7). They also have consistent
649 quantities of detrital clay and grain-coating microcrystalline quartz (Table 1). Sam-
650 ples that have been fully cemented with early diagenetic calcite, i.e. with all pore
651 space filled very soon after deposition, have been removed from the analysis since
652 they cannot record the effects of oil emplacement of burial diagenetic processes. The
653 amounts of ferroan dolomite observed in pores are approximately consistent for the
654 different facies (Table 1). The quantity of petrographically-defined quartz cement has
655 been plotted against specific water saturation for each sample, derived using log data
656 with the data split by the petrographically-defined microquartz content (Fig. 18).
657 This approach shows that low water saturations (and therefore high oil saturations)
658 equate to less quartz cement in medium-grained graded facies 1 (Fig. 18a) and fine-
659 to medium-grained bioturbated facies 2 (Fig. 18b), relative to samples of these same

660 facies from the water leg. There does not appear to be a simple relationship between
661 water saturation and quartz cement content for very fine to fine bioturbated facies 3
662 (Fig. 18c) although large quantities of microquartz in this facies equate to negligible
663 amounts of quartz cement in all cases. The lack of correlation of water saturation
664 with quartz cement for the very fine to fine bioturbated facies may be a result of: (1)
665 the large quantity of pre-existing detrital clay that left less room for quartz cement to
666 grow (Fig. 12; Table 1), or (2) the great abundance of grain-coating microquartz that
667 prevented quartz cement precipitating (Figs. 12, 14, 18c; Table 1).

668

669 Focusing on the medium-grained graded facies 1 sandstones that have less than 20%
670 grain coating, it is possible to discern a good correlation between water saturation
671 and quartz cement content (Fig. 19a). There are good inverse relationships between
672 water saturation and core analysis porosity and permeability (Figs. 19b-c). There is
673 also a good inverse relationship between quartz cement and core analysis porosity
674 (Fig. 19d) confirming that quartz cement is the master control on reservoir quality.

675

676 The conclusion from the data detailed in Table 1 and Figures 18 and 19 is that for
677 medium-grained graded facies 1 sandstones, that have virtually identical and small
678 amounts of detrital clay, ferroan dolomite, and grain-coating microquartz, samples
679 from the oil leg appear to have less quartz cement, higher porosity and higher perme-
680 ability than samples from the water leg. The same is broadly true for fine- to medi-
681 um-grained bioturbated facies 2 sandstones (Table 1) but very fine to fine
682 bioturbated facies 3 samples tend to have a relatively small quantity of quartz cement
683 irrespective of oil saturation. Facies 3 sandstones have smaller quantities of quartz
684 cement than facies 1 and 2 due to the combined effects of grain coating microquartz

685 (Fig. 14) and relatively minor extra amounts of ferroan dolomite and abundant matrix
686 clay (Table 1).

687

688 The assessment of the effects of compaction versus cementation (Fig. 17) shows that
689 water leg samples tend to be more cementation-dominated than oil leg samples. For
690 samples of the same facies, with the same microquartz content, this difference is the
691 result of there being more quartz cement in the water leg than the oil leg (Fig. 18a).
692 We can thus surmise that the growth of quartz cement in the oil leg has been inhibit-
693 ed relative to growth in the water leg.

694

695 ***Synthesis: has oil slowed quartz cementation and therefore caused***
696 ***preservation of porosity?***

697 The key question addressed by this study is whether emplacement of oil during
698 diagenesis led to inhibition of quartz cementation in the Ula Formation in Ula Field.
699 Samples from the oil leg have higher porosities and less quartz cement than compa-
700 rable samples from the water leg for facies 1 and facies 2 (Table 1, Fig. 18). This dif-
701 ference cannot be explained by demonstrable variances in abundance of microcrys-
702 talline quartz coatings (Figs. 12 and 14), grain size, grain-coating chlorite or the
703 presence of other subordinate pore-filling cements (Table 1). We therefore propose
704 that the differences in porosity and quartz cement abundance as a function of oil sat-
705 uration may be directly attributed to differences in the dominant fluid type within the
706 pore space of these samples.

707

708 In essence, the rate of quartz cement growth will be limited to the slowest step in the
709 sequence of steps: supply, transport and precipitation. Having oil present in the pore
710 space during quartz cementation (as shown by oil inclusions in quartz cement; Figs.
711 15, 16) may have caused the rate of quartz *precipitation* to slow significantly relative
712 to similar samples with high water saturation and therefore led to less quartz cement
713 being precipitated. However, the recorded reduced abundance of quartz cement in the
714 oil leg samples (in medium-grained graded facies 1 and fine- to medium-grained
715 bioturbated 2) could also be the result of reduced rates of silica *supply* in the oil leg
716 (presumably from internal, stylolite-related sources). Alternatively, there may have
717 been reduced rates of silica *transport* in the presence of oil due either to slowed ad-
718 vection (resulting from relative permeability effects) or slowed diffusion (resulting
719 from tortuosity effects) (Worden et al., 1998). The lack of correlation between IGV
720 and quartz cement content (Table 1, Appendix 1) could be used to infer that pressure
721 solution (chemical compaction) has not been affected by the emplacement of oil if
722 we assume that quartz cement was only supplied by local, intra-facies pressure solu-
723 tion. However we cannot be sure that quartz cement in facies 1 and 2 sandstones has
724 not been supplied by feldspar-clay reactions (Barclay and Worden, 2000b), pressure
725 solution in surrounding mudstones (Land and Millken, 2000) or clay-rich sandstones
726 (Trewin and Fallick, 2000), export of biogenic silica from finer sandstone facies (e.g.
727 facies 3) (Worden and Morad, 2000) or even mass flux from deeper in the basin
728 (Giles et al., 2000). Although we cannot be sure which of supply, transport and pre-
729 cipitation rate has been slowed by the presence of oil we can state that the overall
730 process of quartz cementation has been significantly slowed in cleaner, less fine-
731 grained, minimally microquartz-coated sandstones, by the presence of oil in the pore
732 network.

733

734 **Conclusion**

- 735 1. Oil was present during quartz cementation in the Ula Formation in Ula
736 Field as revealed by the presence of oil inclusions suggesting oil ingress
737 into the reservoir began when the reservoir was at a temperature of about
738 100-120°C.
- 739 2. Aqueous fluid inclusion homogenisation temperature data from primary
740 inclusions in quartz cement shows that quartz cementation seems to have
741 started at an absolute minimum of 103°C with most quartz cement grow-
742 ing at >120°C, if assume that the lower homogenisation temperatures for
743 aqueous inclusions in quartz are regarded as being representative of mini-
744 mum growth temperature.
- 745 3. For sandstones of the same depositional facies, with similar grain size,
746 similar detrital clay content, similar low quantity of grain coating micro-
747 quartz and similar low quantity of ferroan dolomite, there is less quartz
748 cement in the oil leg than in the water leg, particularly for facies 1 (me-
749 dium-grained graded sandstone) and facies 2 (fine- to medium-grained
750 bioturbated sandstone).
- 751 4. For facies 3 (fine- to very fine-grained bioturbated sandstone) there ap-
752 pears to be little quartz cement, regardless of whether oil was present dur-
753 ing diagenesis or not. This can be attributed to the (relatively) large quan-
754 tity of grain-coating microquartz and detrital clay associated with this fa-
755 cies.

- 756 5. A small number of the coarse-grained sandstone samples in the water leg
757 also have a few percent grain-coating microquartz. These have unusually
758 reduced quantities of quartz cement showing that microquartz, as well as
759 oil emplacement, can inhibit quartz cementation.
- 760 6. Emplacement of oil before, or during, quartz cementation has inhibited the
761 growth of quartz cement in the Ula Formation in the cleaner, fine- to me-
762 dium-grained and medium-grained graded, minimally microquartz ce-
763 mented sandstones.
764

765 **FIGURE CAPTIONS**

766 Figure 1. Location map of the Central Graben showing Ula Field with insert map of
767 the North Sea region (lower left). The map shows the study area in the black square
768 and inserted field structural map right showing major bounding faults structures and
769 well locations (modified from Nedkvitne et al., 1993).

770 Figure 2. Generalized stratigraphy of Ula Field. The Mandal Formation is the main
771 regional source rock; the Ula Formation is the reservoir under consideration.

772 Figure 3. Thermal curves for Ula Field from well 7/12-6 (Fig. 1), the heavier black
773 line represents the top of the Ula reservoir interval. The combined burial and thermal
774 history was modelled using BasinMod software.

775 Figure 4. Comparison of core analysis porosity and wireline-derived porosity for
776 well 7/12-A13.

777 Figure 5. Plots of density-derived porosity and Archie-derived water saturation (S_w)
778 from four of the five Ula field wells used in this study.

779 Figure 6. Plots of core analysis porosity and permeability subdivided by wireline
780 derived water saturations for the three facies; (a) Medium-grained graded sandstone
781 facies, (b) Fine- to medium-grained bioturbated sandstone facies, (c) Very fine- to
782 fine-grained bioturbated sandstone facies.

783 Figure 7. Ternary diagram showing the Ula Formation sandstone classification
784 (McBride, 1963).

785 Figure 8. Generalised paragenetic sequence for the Ula Sandstone in Ula Field (7/12-
786 2, 7/12-A3, 7/12-5, 7/12-A08 and 7/12-A13). Age ranges of diagenetic phases are
787 estimated based on thin section and SEM observations.

788 Figure 9 a) SEM image showing framboidal pyrite (py) and microcrystalline quartz
789 (μ qz) formed early within intergranular area (7/12-A3, 3520.36 m TVD, Sw 0.61) b)
790 SEM image showing partial dissolution of detrital K-feldspar grain (KF) and later
791 authigenic quartz within the secondary intragranular pore (sip) (Well 7/12-5, 3894.00
792 mDD, Sw 0.78). (c) quartz overgrowth (qzo) encloses pore-filling chlorite (ch)
793 shown by circle (Well 7/12-5, 3894.00 mDD, Sw 0.78) suggesting quartz
794 precipitation after chlorite. (d) late hairy illite (i) draped quartz overgrowths (7/12-
795 A3 , 3520.36 m TVD, Sw 0.61). (e) Optical thin section photomicrograph (plane
796 polarised) showing feldspar overgrowths (kfo) and quartz overgrowths both of which
797 thin at grain contacts (circled) suggesting precipitation after main phase of
798 compaction (7/12-A3, 3515.76 m TVD, Sw 0.35). (f) residual hydrocarbons (rh)
799 which stain earlier quartz overgrowths (7/12-2, 3407.93 m TVD, Sw 0.06).

800 Figure 10 (a) Thin section photomicrograph (plane polarised light) showing patchy
801 clay minerals (PC) and dolomite cement (dol) (7/12-2, 3389.92 m TVD, Sw 0.05).
802 (b) Thin section image (plane polarised) showing quartz overgrowths which partially
803 fills primary intergranular pore (PP) and stained by residual hydrocarbons (rh) (7/12-
804 2, 3427.67 m TVD, Sw 0.13). (c) Thin section photomicrograph (plane polarised
805 light) showing clean primary porosity (PP) medium to high volume of quartz
806 overgrowths (qzo) and uncoated quartz grain (Q) (7/12-A13, 3706.32 m TVD, Sw
807 0.62). (d) Thin section photomicrograph (plane polarised light) showing quartz
808 overgrowths (qzo) occluding primary pores around quartz grain 7/12-A3, 3525.35 m

809 TVD, SW 0.31). (e and f) Backscattered electron image and cathodoluminescence
810 image of the same sample differentiating between detrital quartz (Q) and quartz
811 overgrowths (qzo) in the later. Note that it much easier to observe quartz cement-
812 grain boundaries using light optical images than backscattered electron images.
813 (7/12-A3, 3525.35 m TVD, SW 0.31).

814 Figure: 11. SEM micrographs of minimally quartz cemented samples of medium-
815 grained graded facies 1 from the oil leg revealing the lack of microquartz or any
816 other sort of grain coating material. The exposed quartz grain surfaces contain
817 nascent quartz cement but are largely in their original, depositional, state. qzo:
818 quartz overgrowth, cs: clean grain surface free of microquartz but also with no quartz
819 cement growing. (a and inset b) 7/12-2, 3389.92 m TVD; Sw 0.05. (c and inset d)
820 7/12-2 3384.98 m TVD depth; Sw 0.05.

821 Figure: 12. Variation of log-derived water saturation, core analysis porosity, quartz
822 cement, microquartz and detrital clay with true vertical depth for all the wells
823 studied. Samples have been split into the three main facies. The diagram represents
824 the aggregation of data from four wells; the data are in depth order and do not
825 represent the stratigraphic succession.

826 Figure 13. (a) Thin section image of microquartz-coated sandstone (7/12-2; 3365.40;
827 m TVD; Sw 0.19). (b) SEM image showing grain-coating microcrystalline quartz
828 (μ qz) and mesoquartz (mqz) crystals (7/12-A3; 3534.87 m TVD; Sw 0.55).

829 Figure14. Point-counted quartz cement plotted against: (a) point-counted microquartz
830 cement for all samples, and (b) for a subset of the samples, the percentage of grains
831 coated with microquartz. Samples with abundant microquartz (and grain coating)
832 have little quartz cement suggesting that microquartz has effectively inhibited quartz

833 overgrowths. However, there are many samples with little microquartz (and grain
834 coating) that also have little low quantities of quartz overgrowths suggesting that
835 there is another factor that has significantly affected the growth of quartz cement.

836 Figure 15. Thin section photomicrograph showing fluid inclusions; see Table 2 for
837 details of samples in the images. (a) Plane polar showing fluid inclusion assemblage
838 in quartz cement. (b) Plane polar photomicrograph showing fluid inclusion rim at the
839 boundary between detrital quartz grain and quartz cement samples from water zone
840 well 7/12-A3. (c and d) petroleum inclusion under fluorescence light samples from
841 oil leg of 7/12-2.

842 Figure 16. Homogenization temperature measurements for aqueous and petroleum
843 inclusions in selected samples of the Ula Formation. Note present-day reservoir
844 temperature is only available for well 7/12-A3

845 Figure 17. Diagram, based on petrographic data, illustrating styles of porosity loss in
846 the Ula Formation (after Houseknecht, 1984). The oil leg samples ($S_w < 0.5$) have
847 relatively more porosity lost to compaction than cementation. In contrast, the water
848 leg samples ($S_w > 0.5$) have more porosity lost to cementation than compaction. This
849 diagram suggests that, on average, the water leg is more cemented than the oil leg.

850 Figure 18. Point-counted quartz cement volume versus wireline-derived water
851 saturation; (a) medium-grained graded sandstone facies 1 (b) fine- to medium-
852 grained bioturbated sandstone facies 2 (c) very fine- to fine-bioturbated facies 3. This
853 diagram shows that the fine- to medium-grained bioturbated and medium-grained
854 graded facies have less quartz cement in samples with low water saturation than
855 those with higher water saturation. This suggests that oil emplacement has inhibited

856 the growth of quartz cement. Note that microquartz coatings also play a role in
857 diminishing the amount of amount of quartz cement.

858 Figure 19. Wireline-derived water saturation values for medium-grained graded
859 sandstone facies 1 samples, that have less than 20% grain coating, compared to
860 quartz cement and core analysis data. (a) Water saturation compared to quartz
861 cement showing that these sandstones have decreasing quartz cement in samples with
862 decreasing water saturations. Sandstones with water saturations less than 0.5 have
863 less than 5% quartz cement; those with water saturations greater than 0.5 have up to
864 15% quartz cement. There is a good correlation between water saturation and quartz
865 cement; this relationship could be used to predict quartz cement as a function of
866 water saturation. (b) Water saturation compared to core analysis porosity showing
867 that these sandstones have increasing porosity with decreasing water saturation. (c)
868 Water saturation compared to core analysis permeability showing that these
869 sandstones have increasing permeability with decreasing water saturation. (d) Quartz
870 cement compared to core analysis porosity showing that less quartz cement equates
871 to higher porosity.

872

873 **TABLE CAPTIONS**

874

875 Table 1. Average values of core analysis horizontal permeability porosity, and point
876 count quartz cement, detrital clay, microquartz and ferroan dolomite volumes for the
877 different facies, subdivided by high and low water saturation. A full listing of all
878 petrographic and related data is available in Appendix 1.

879

880 Table 2. The properties of fluid inclusion samples in different wells of Ula Field.

881

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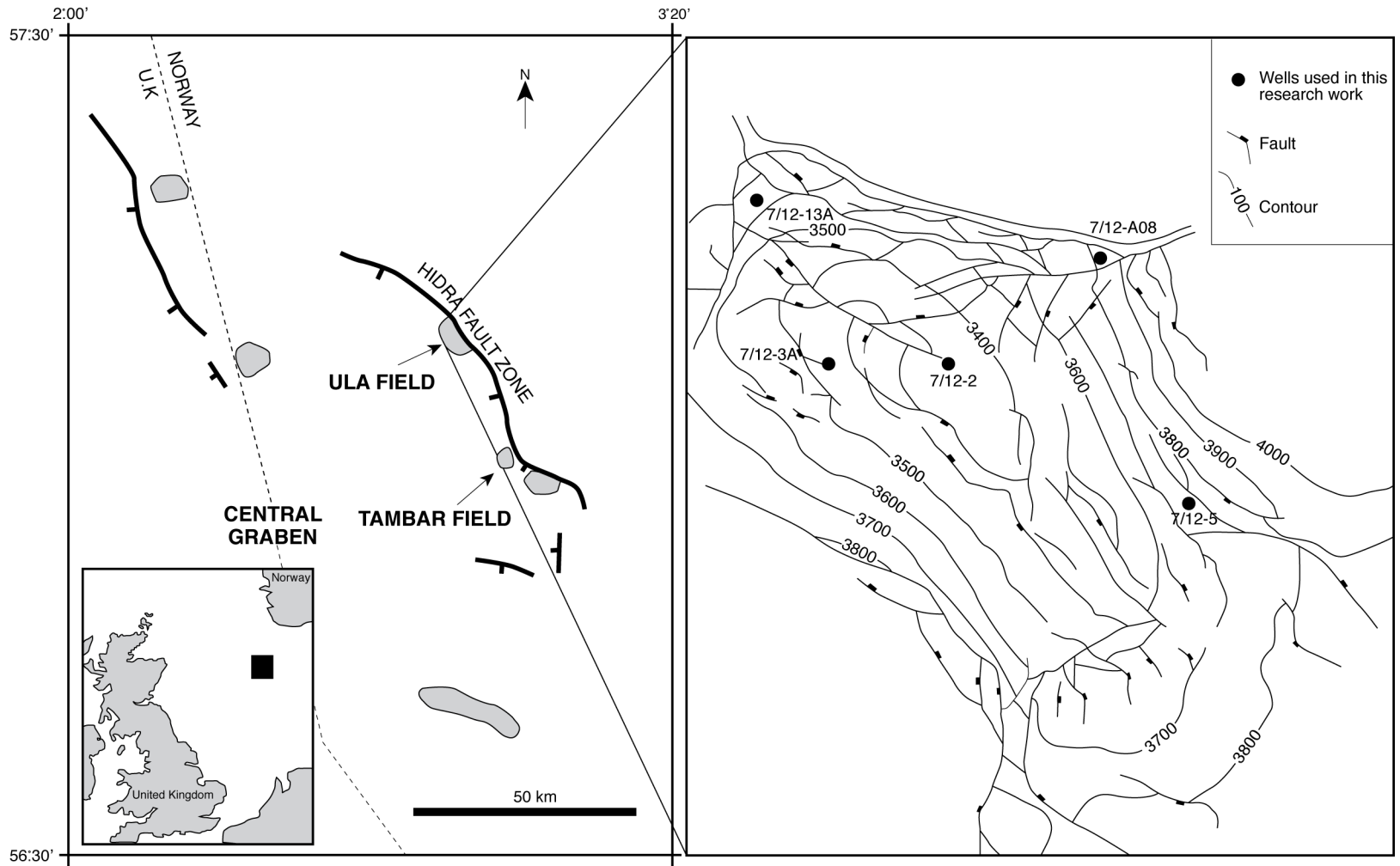


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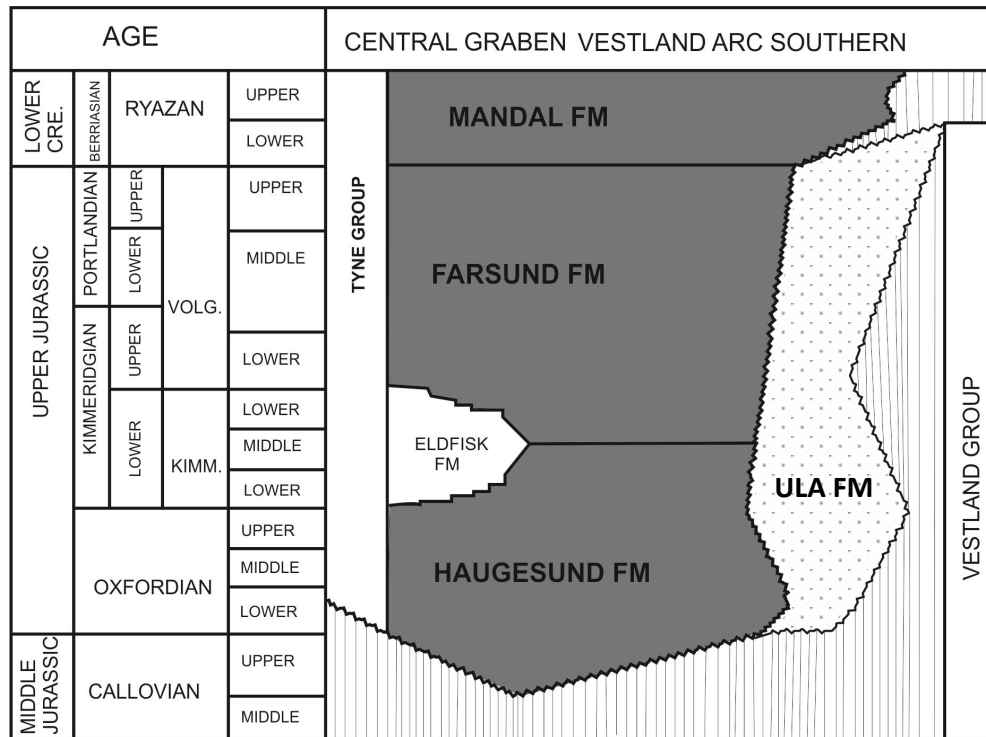


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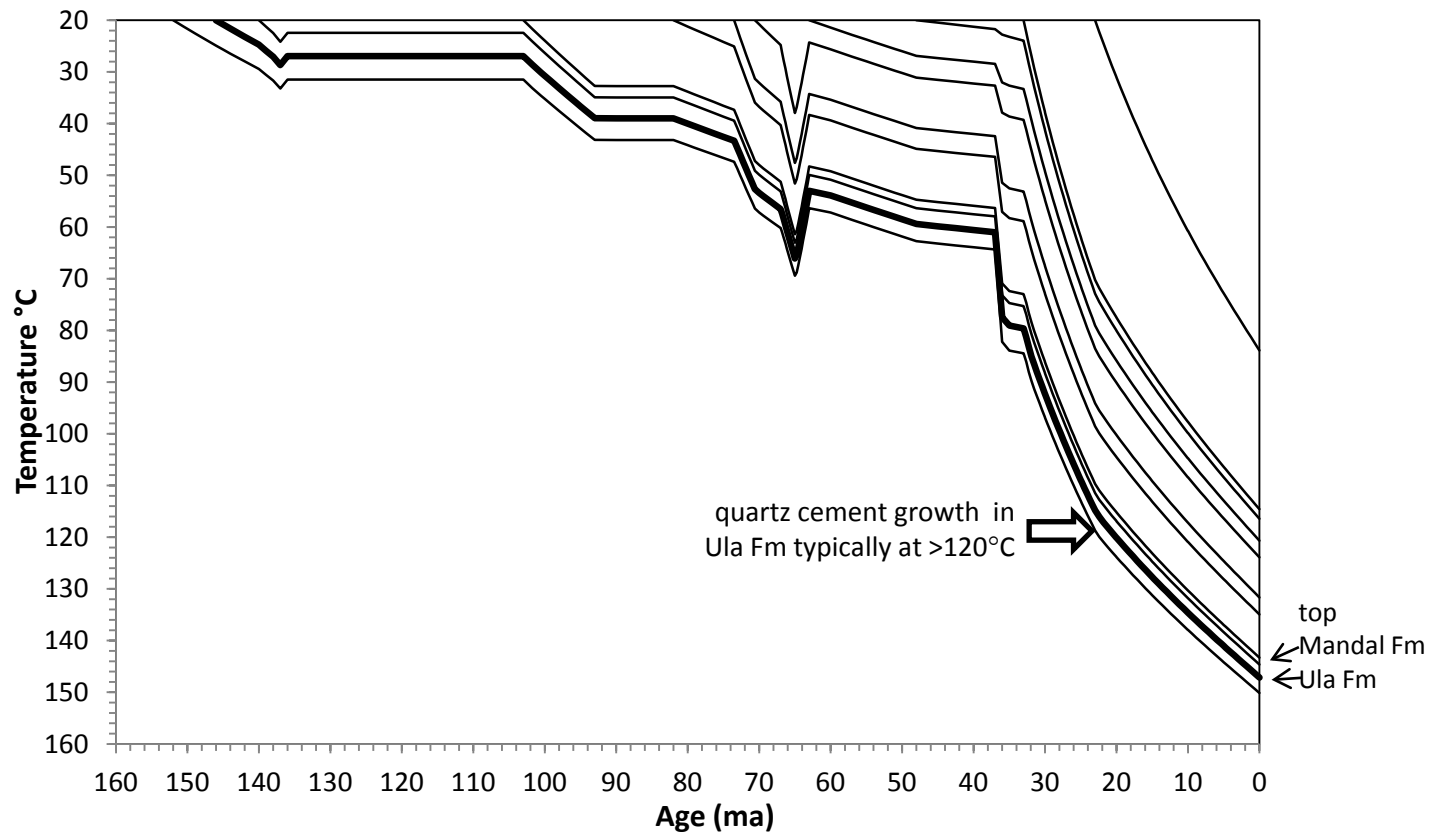


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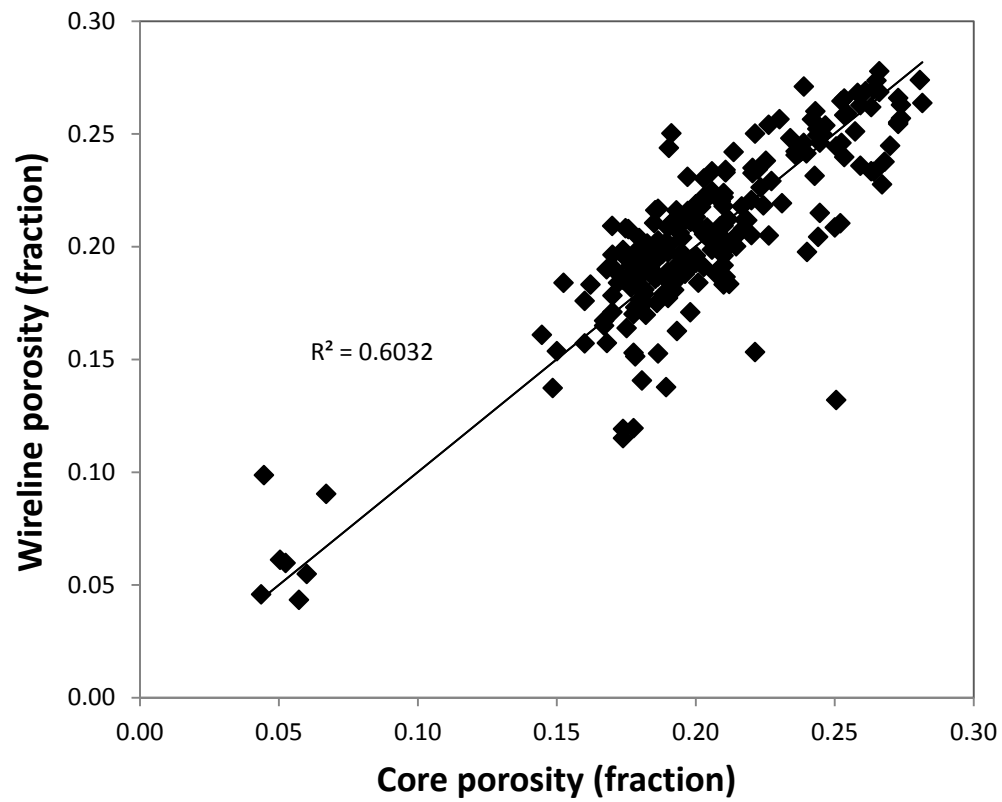


Figure 4

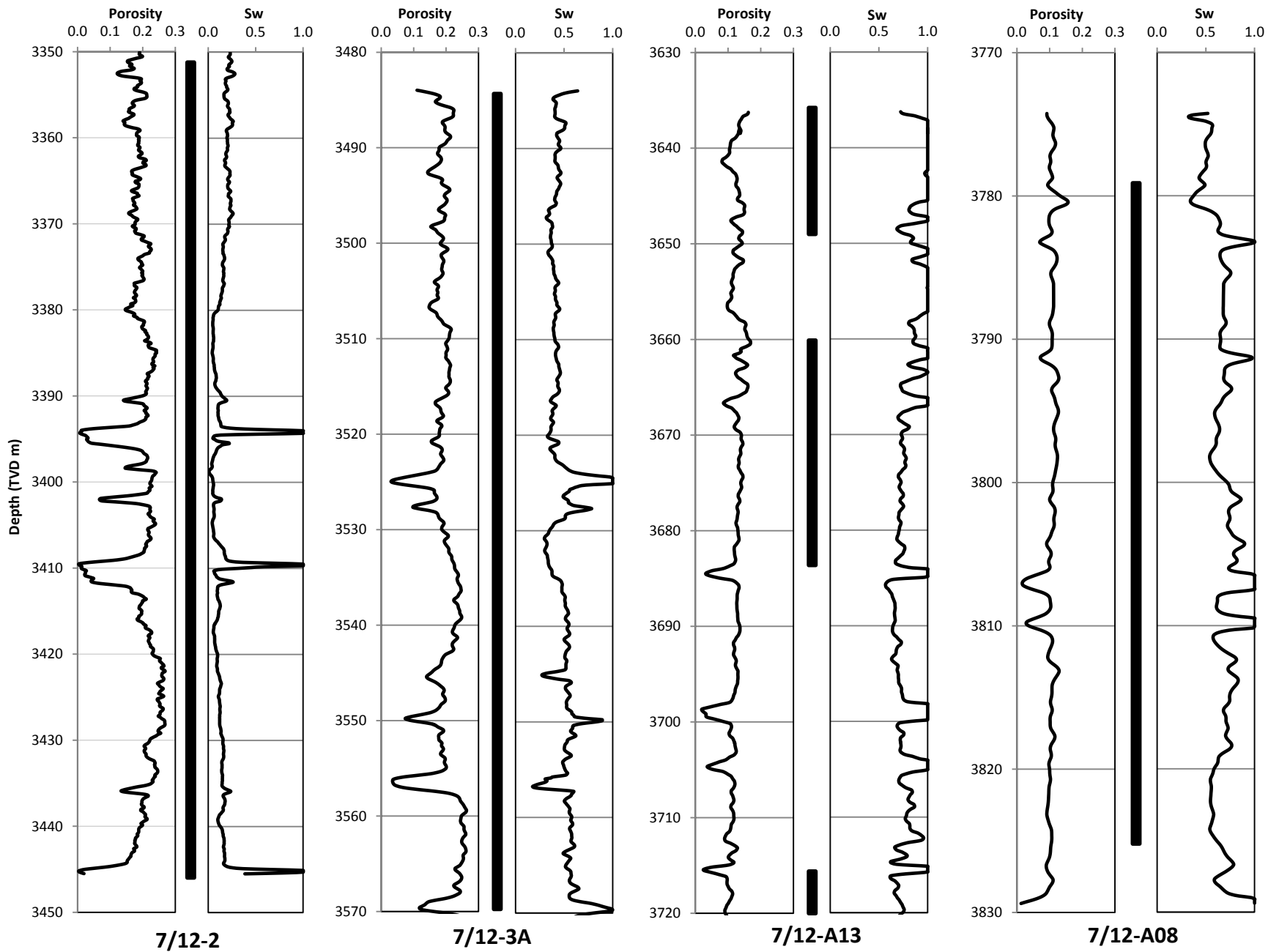


Figure 5

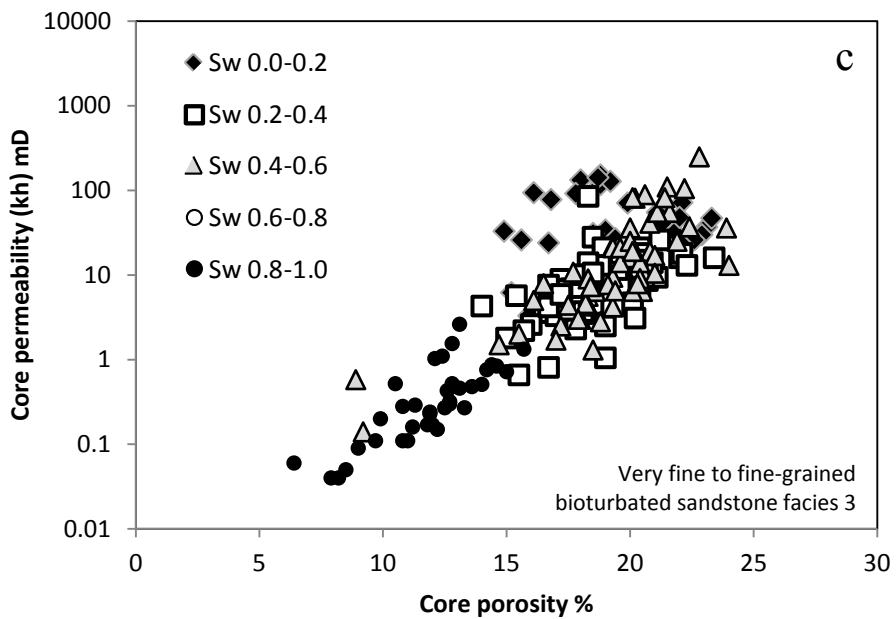
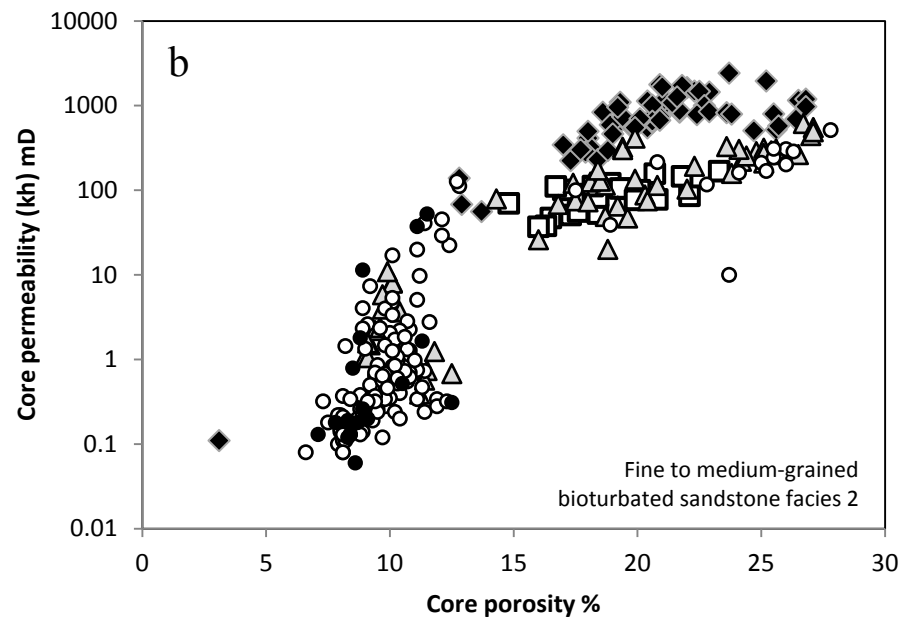
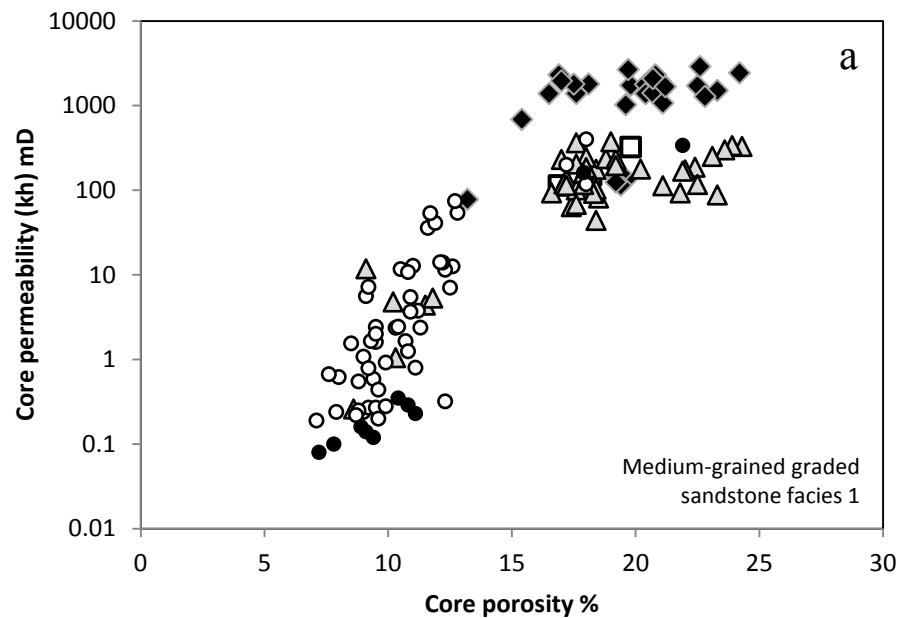


Figure 6

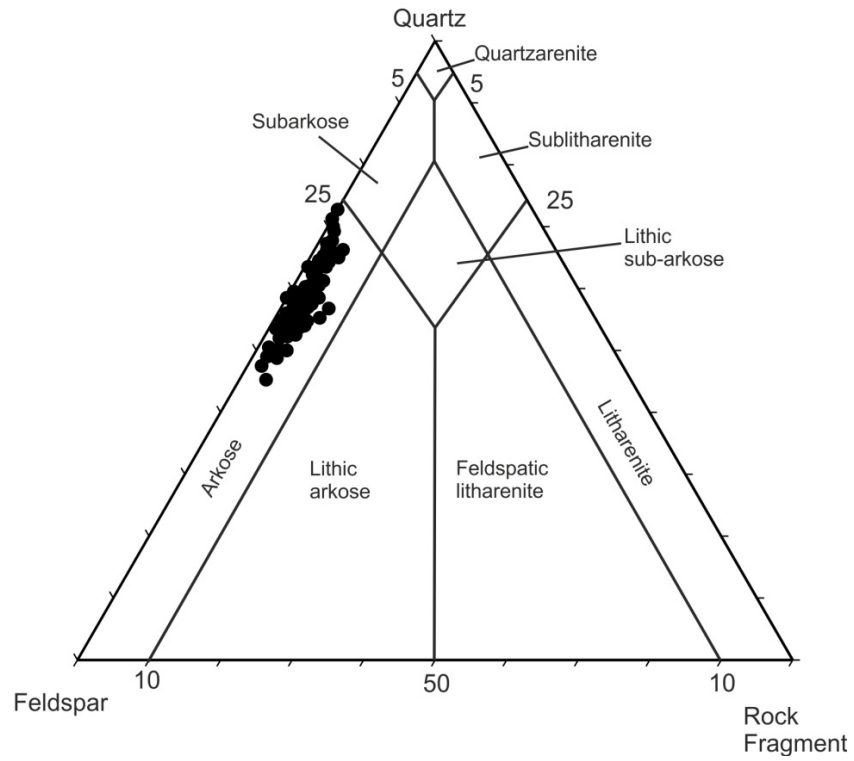


Figure 7

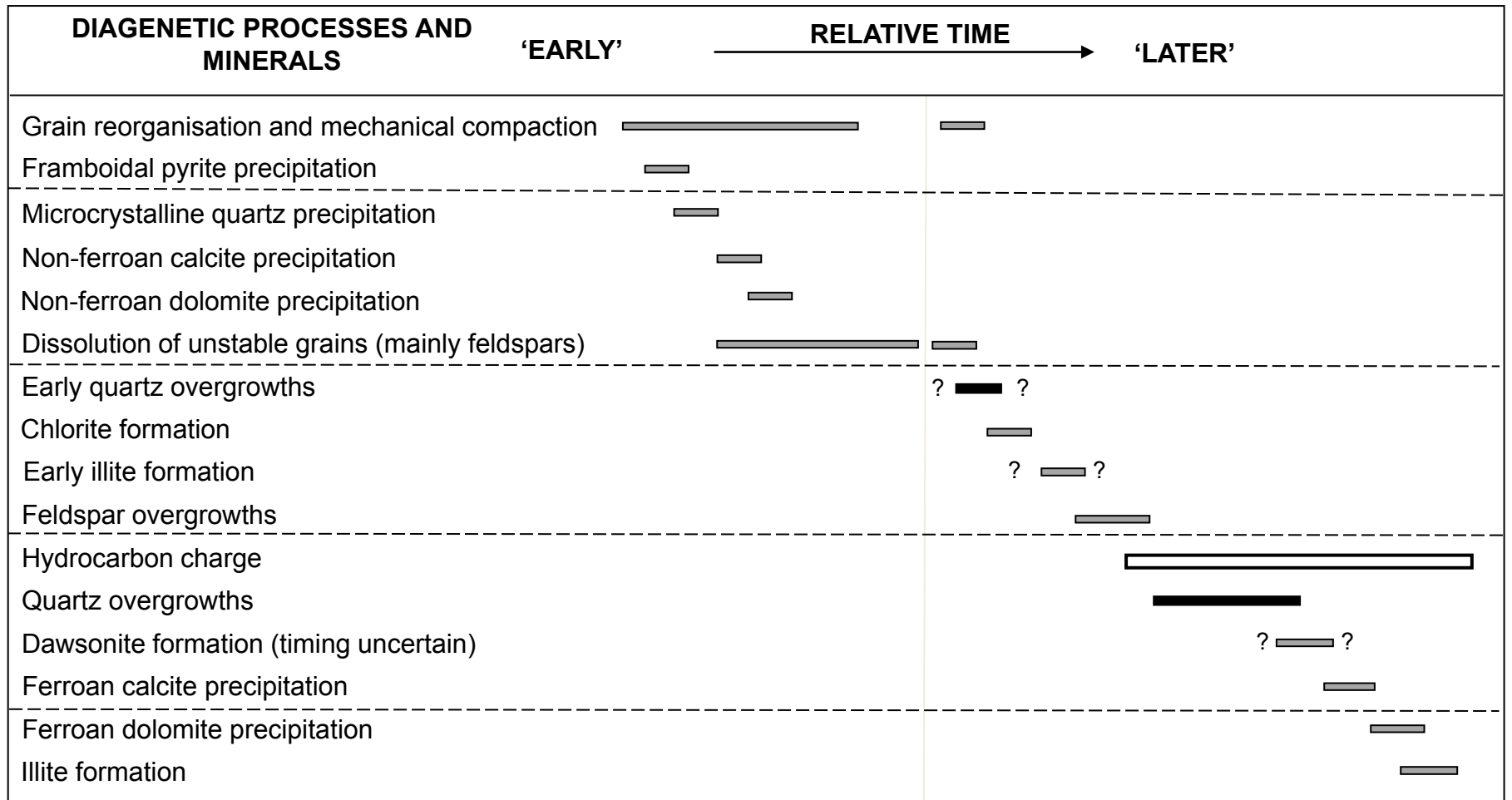


Figure 8

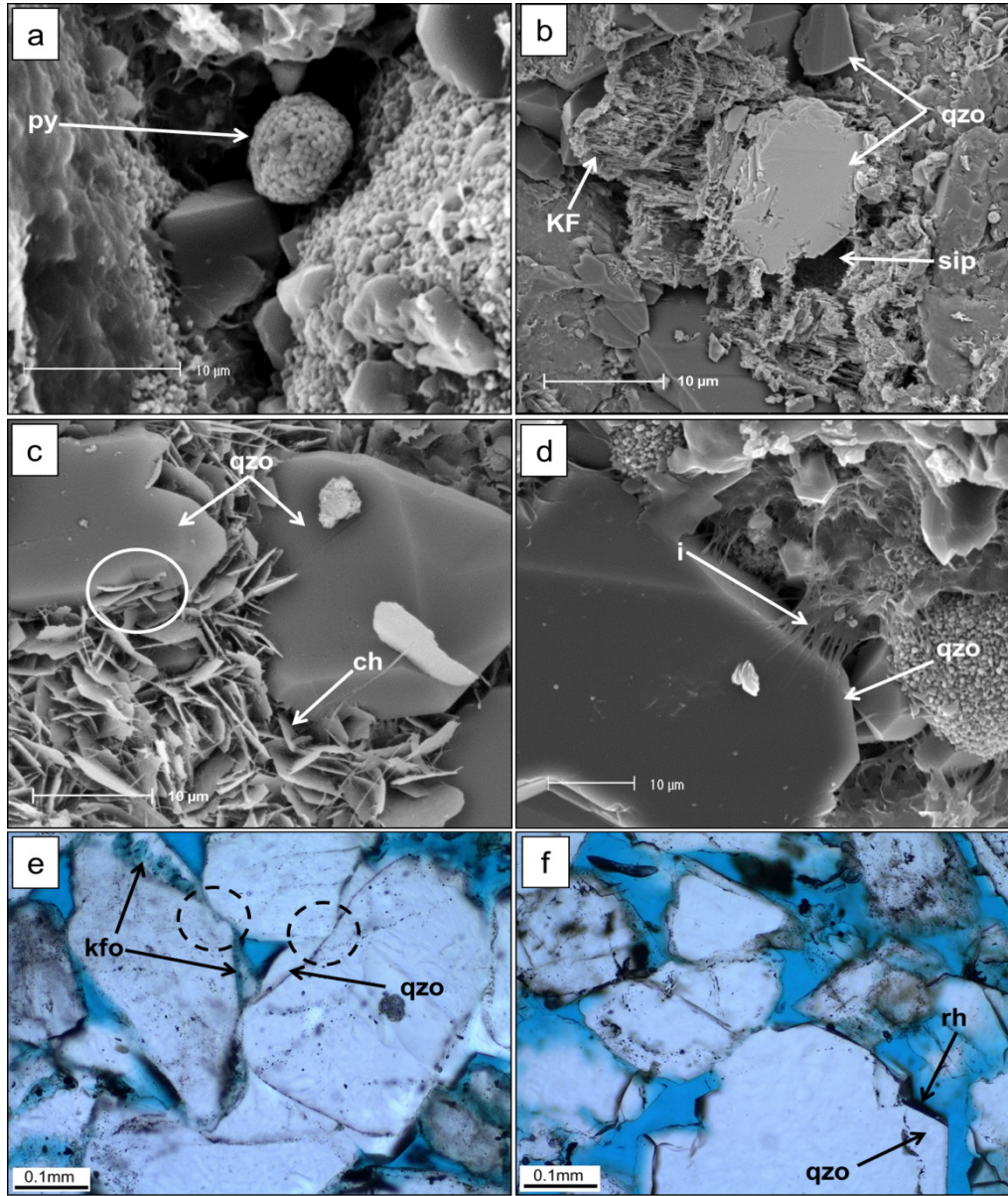


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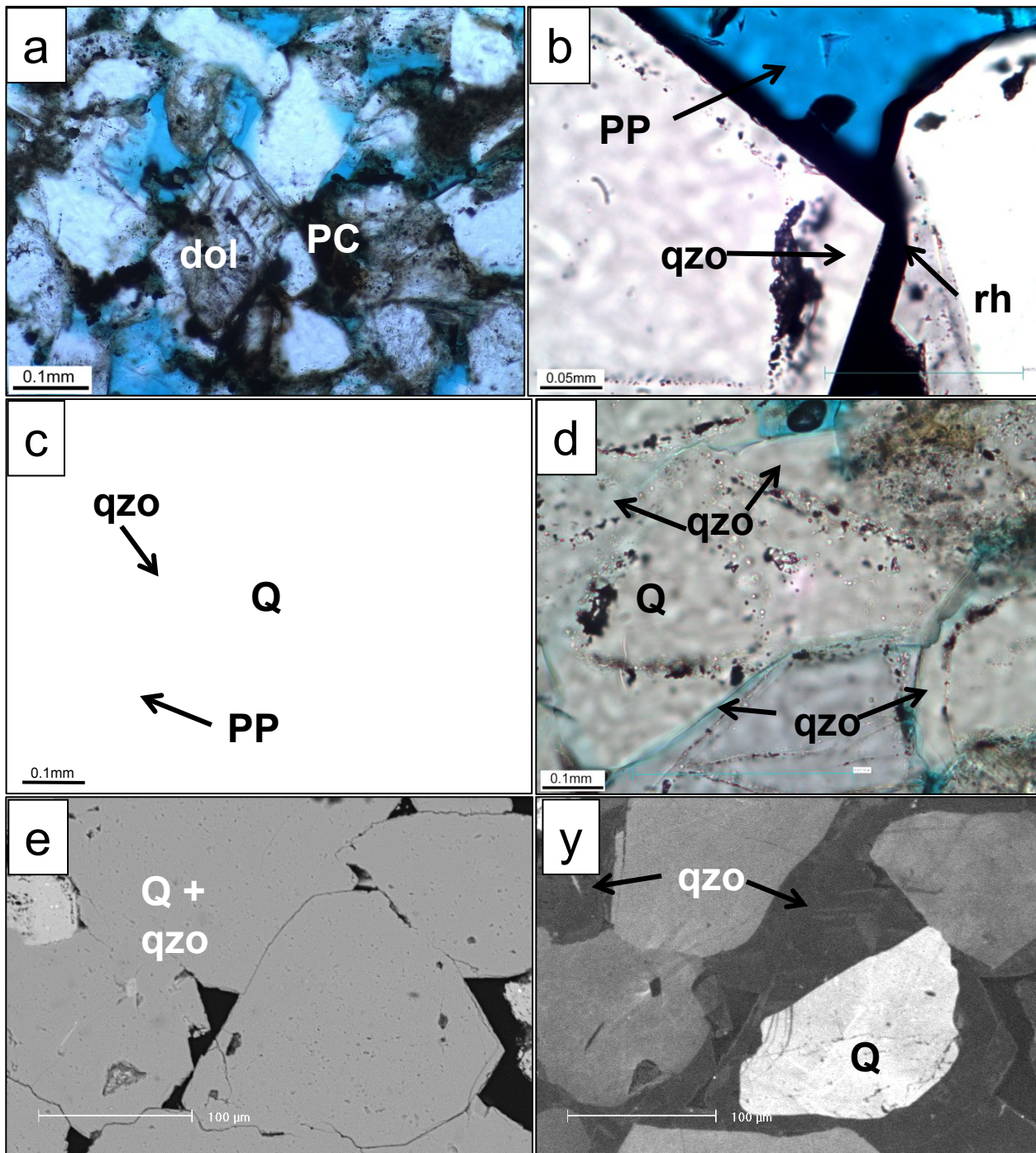


Figure 10

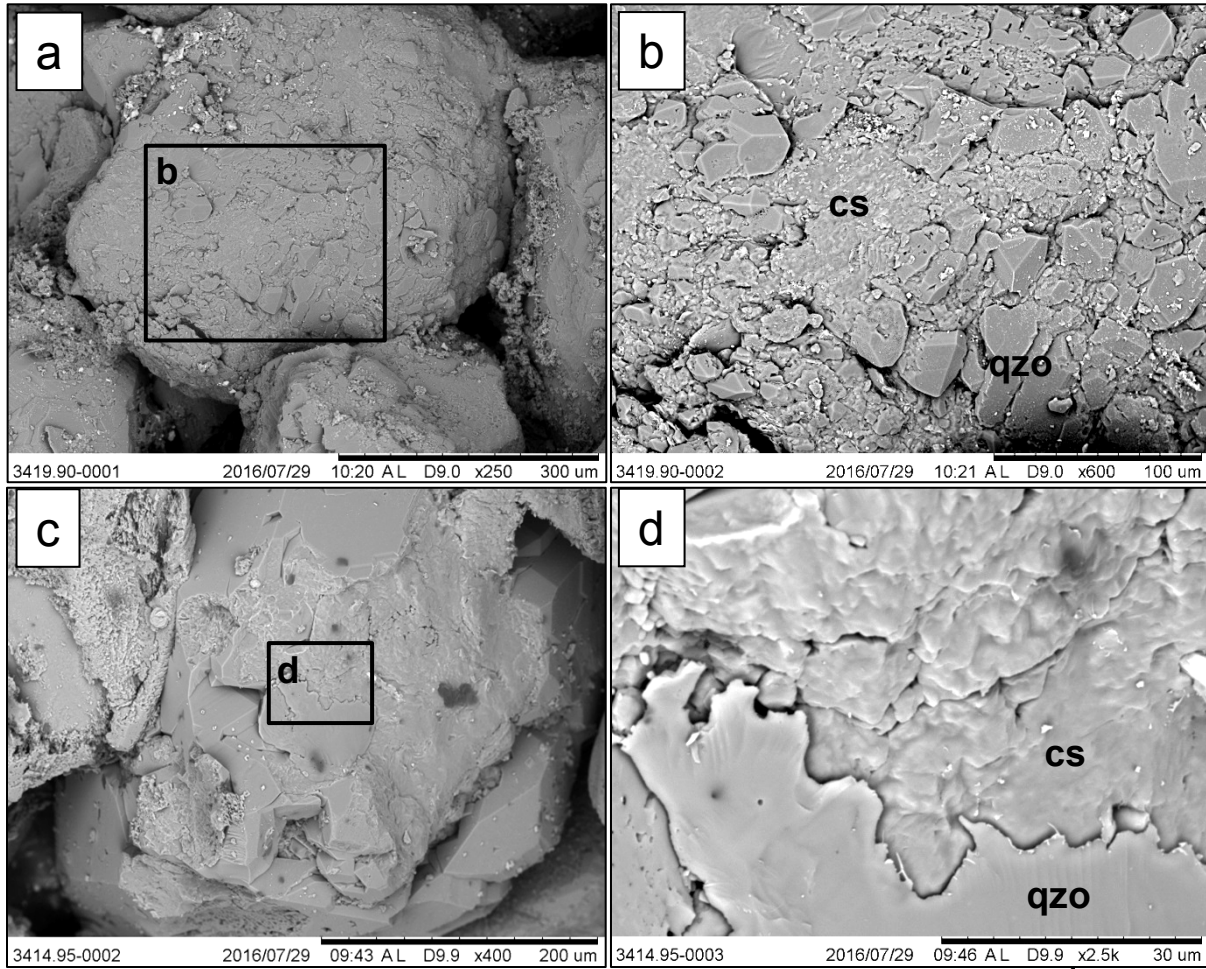


Figure 11

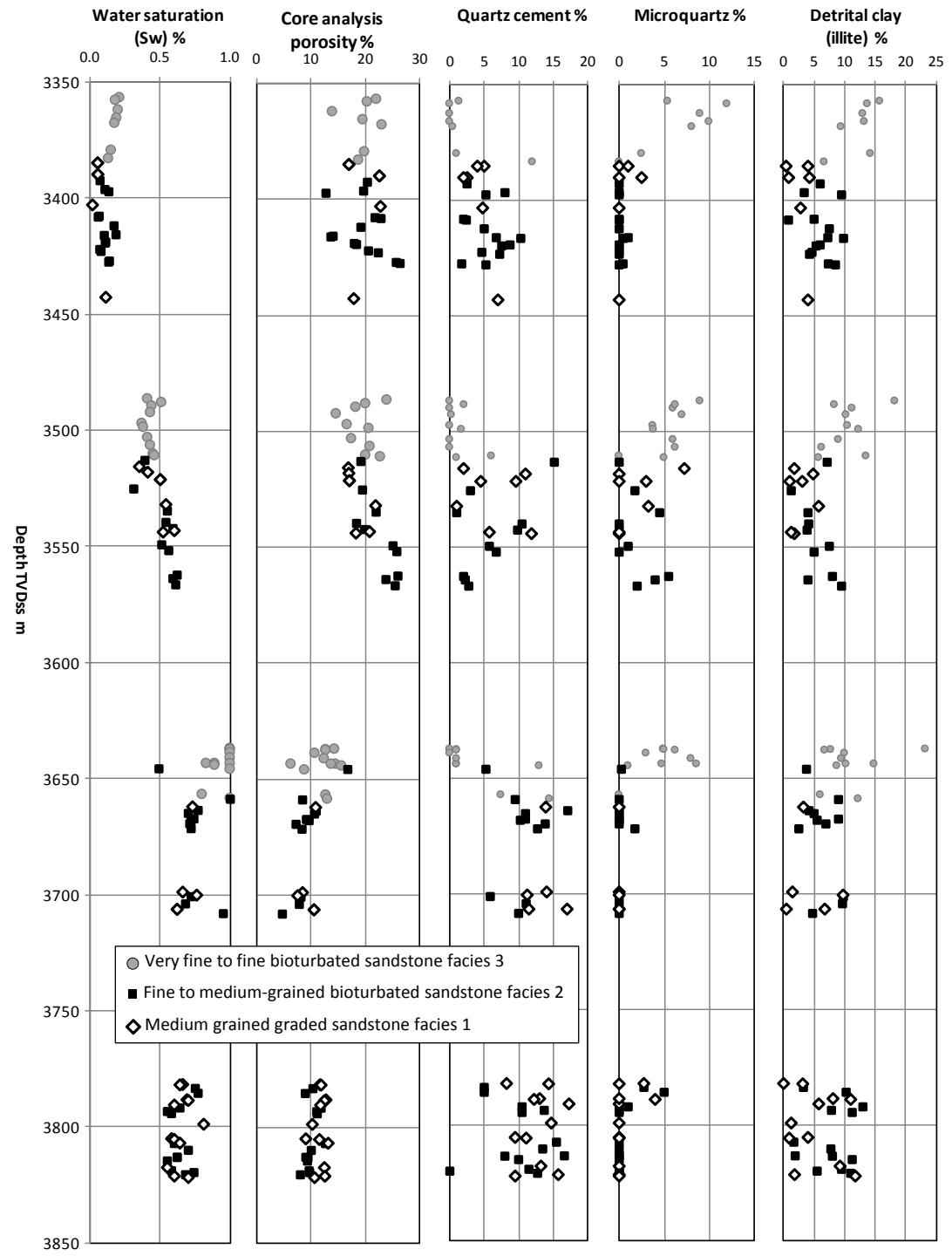


Figure 12

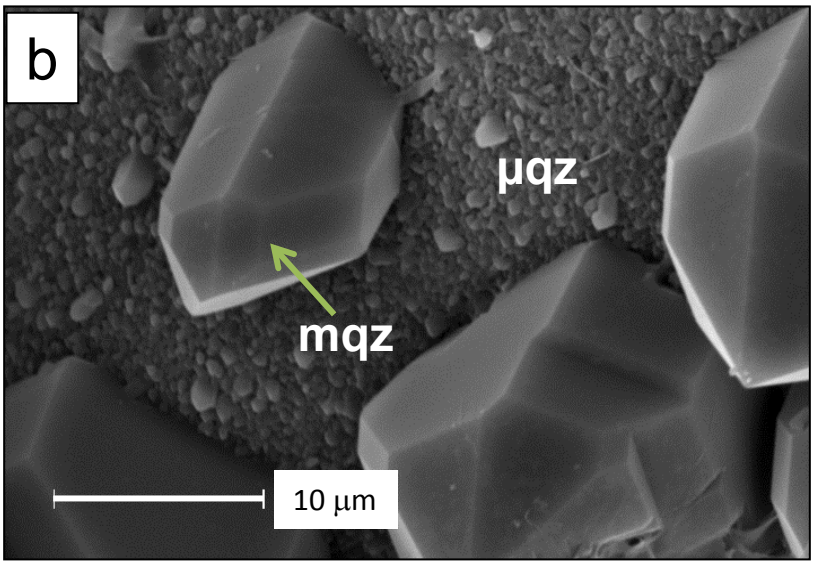
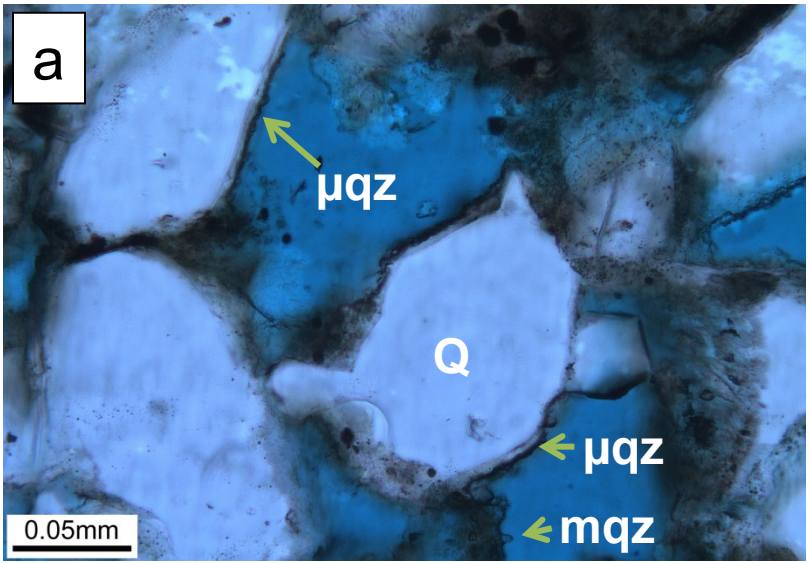


Figure 13

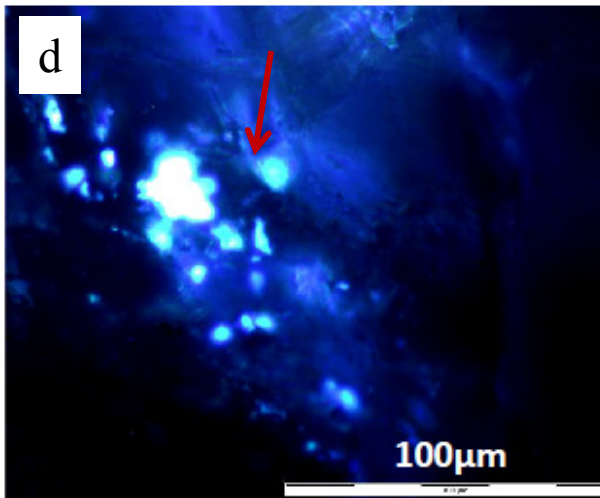
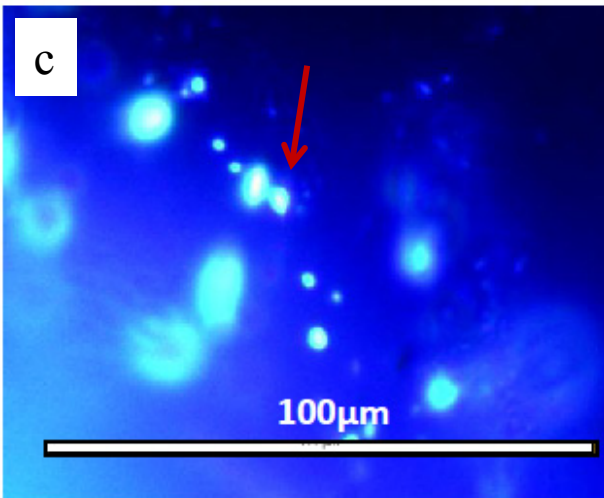
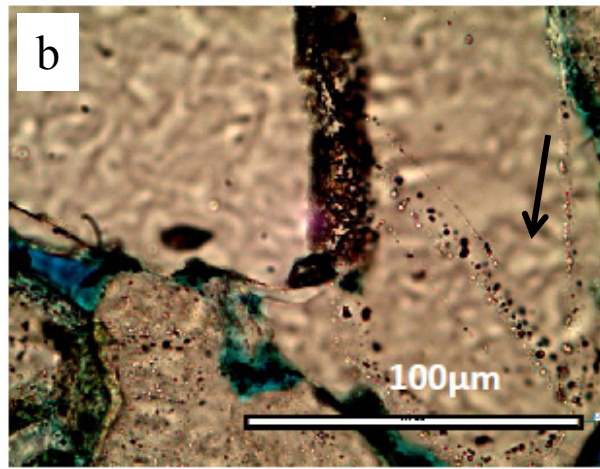
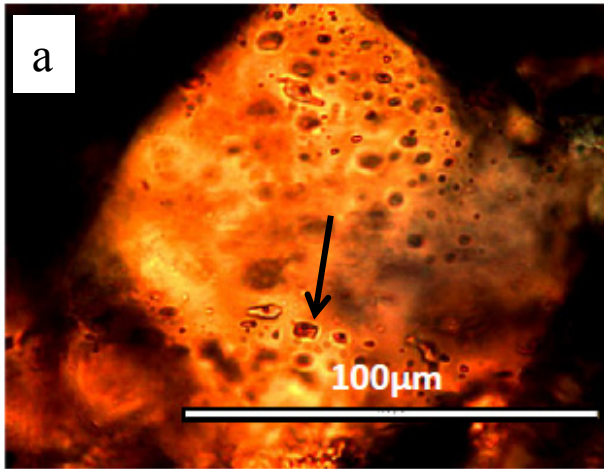


Figure 15

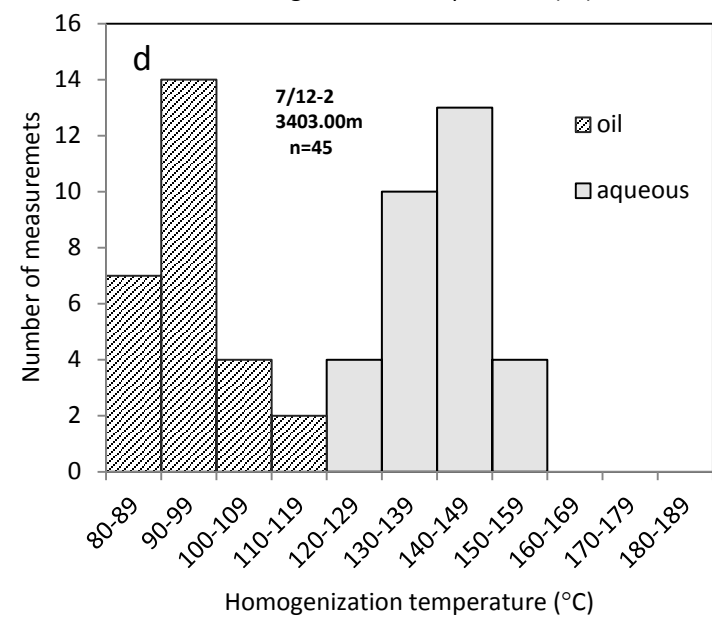
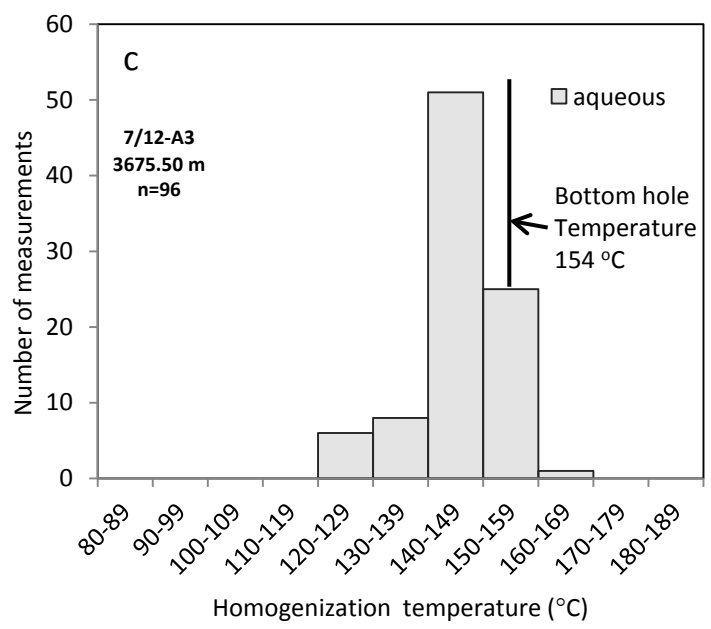
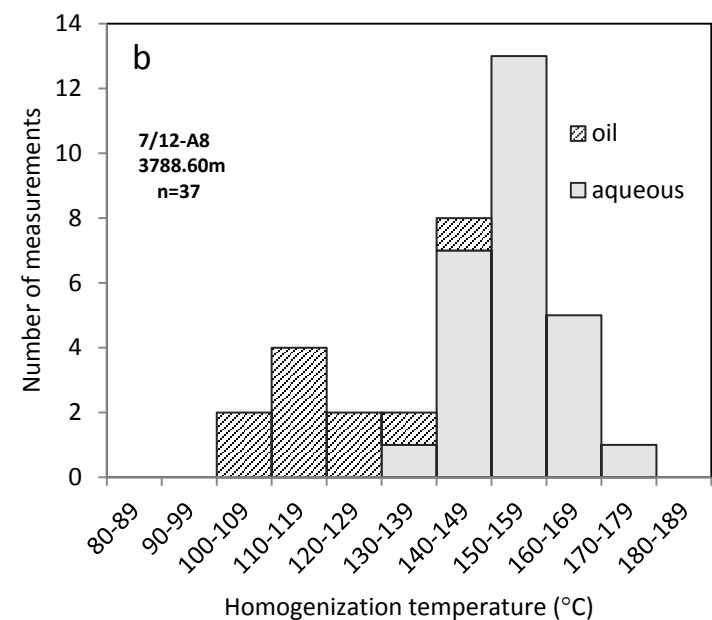
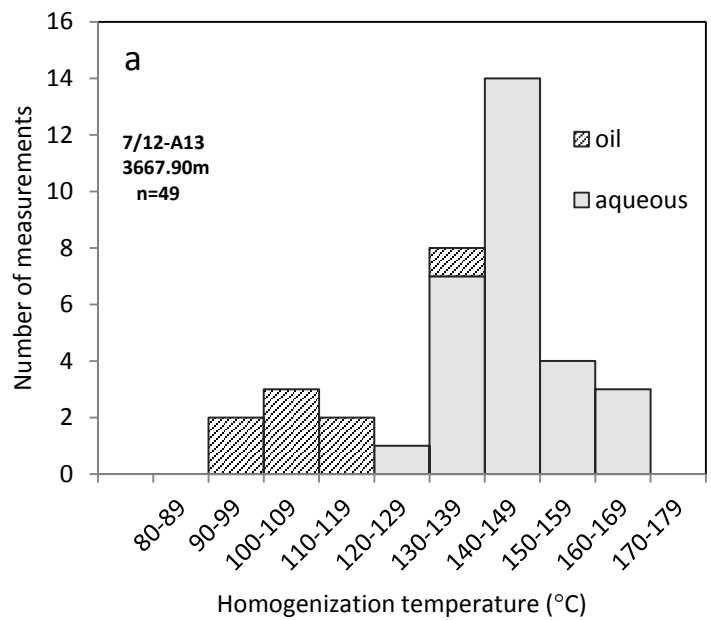


Figure 16

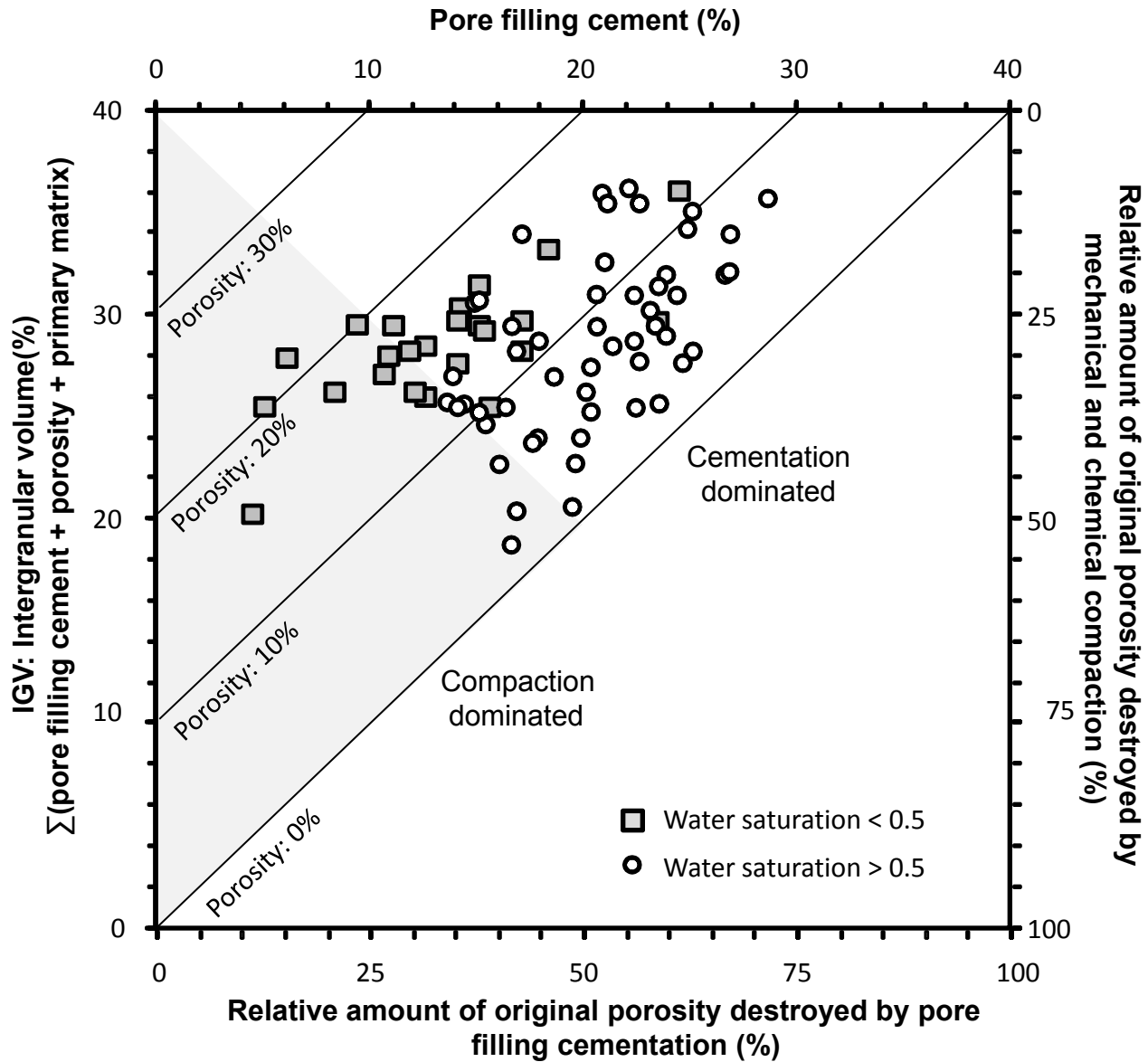
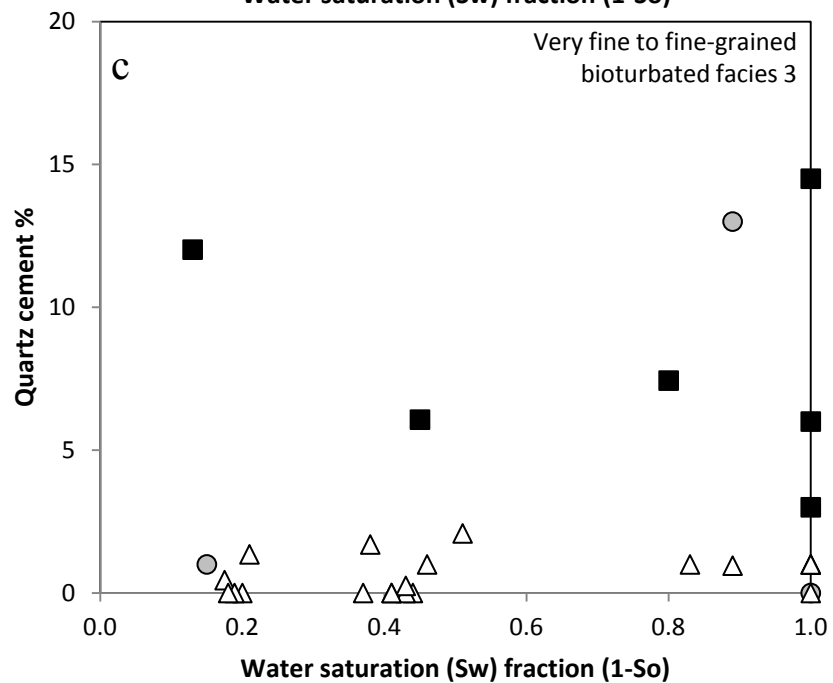
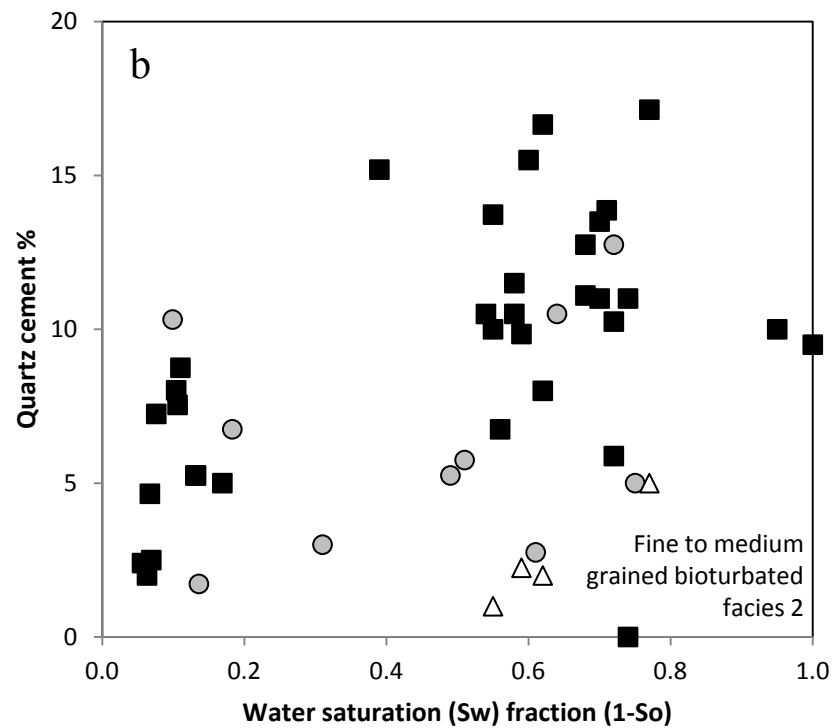
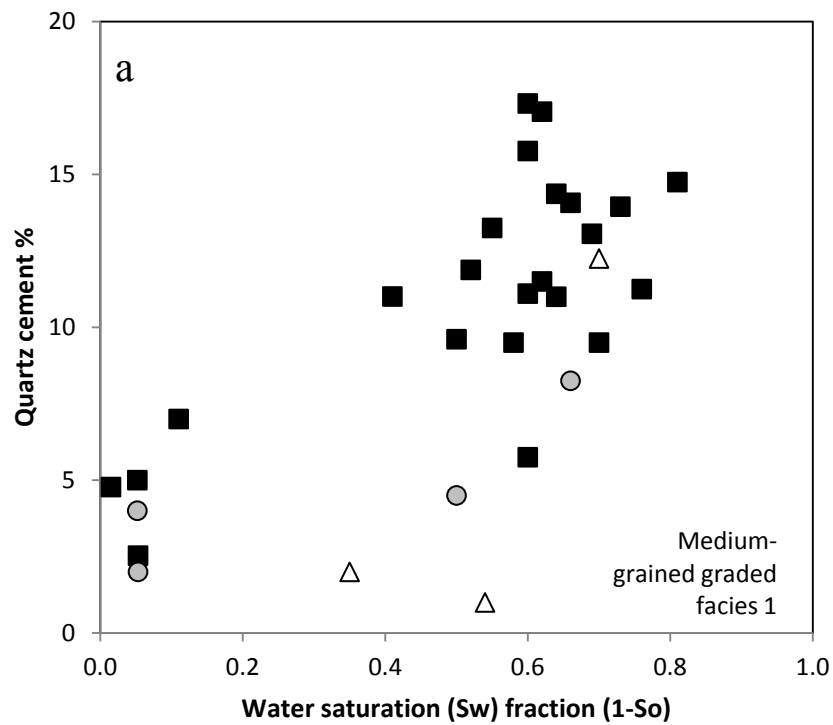


Figure 17



- Microquartz 0%
- Microquartz 0-3%
- △ Microquartz > 3%

Figure 18

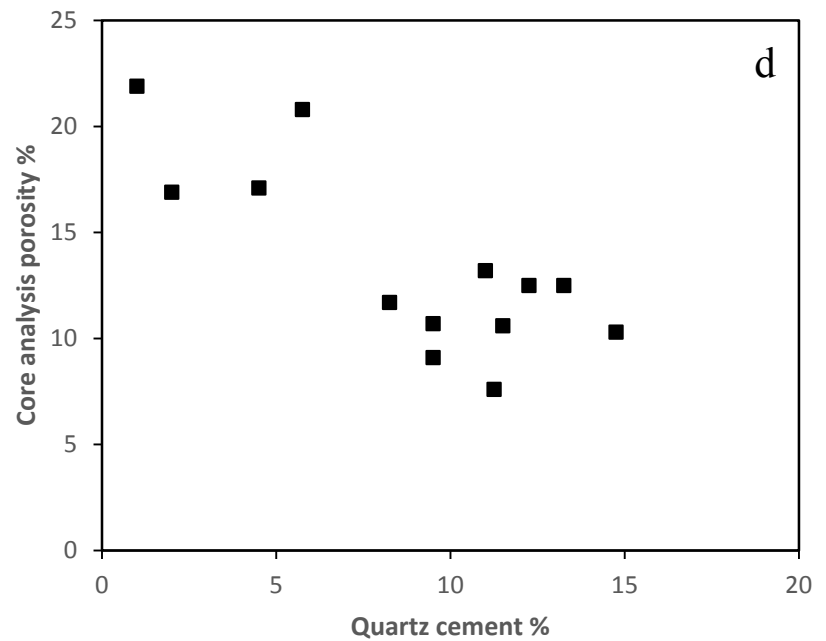
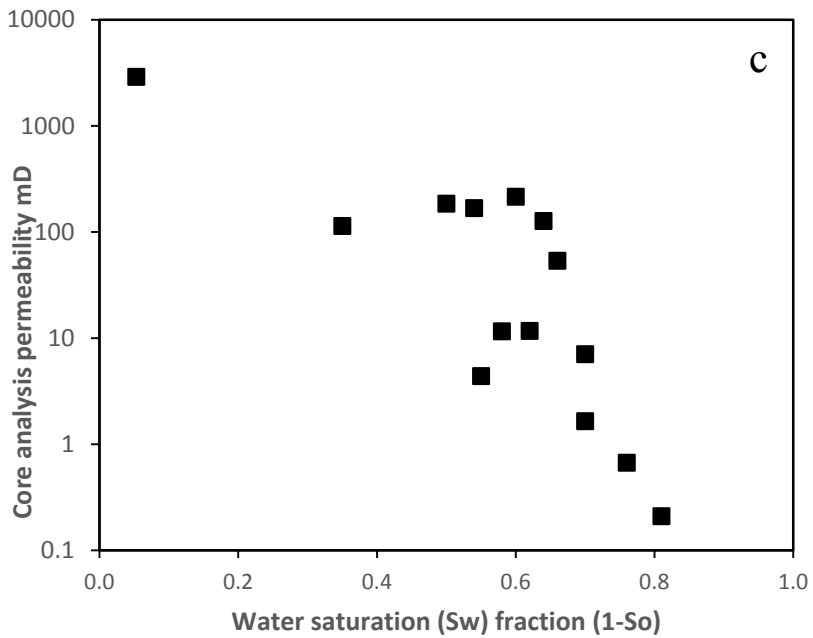
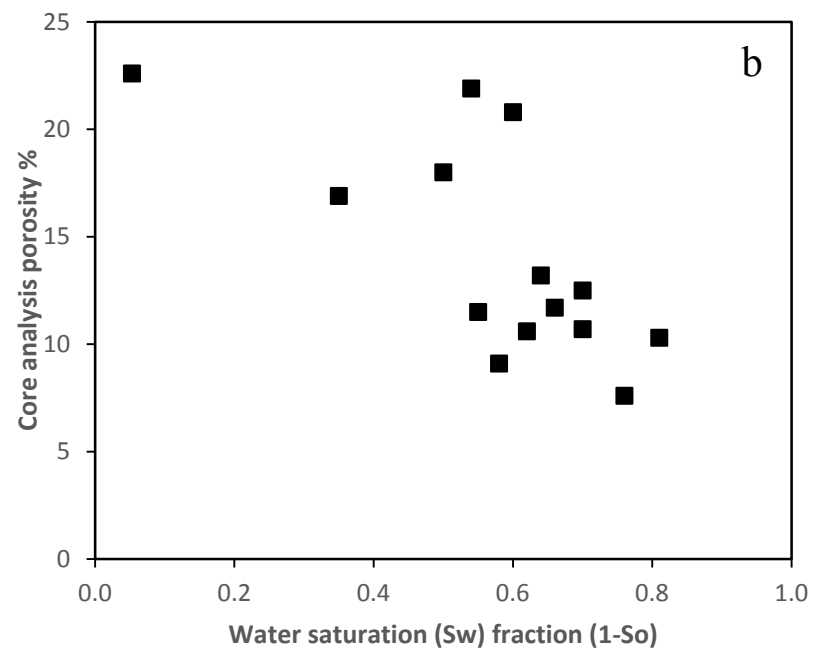
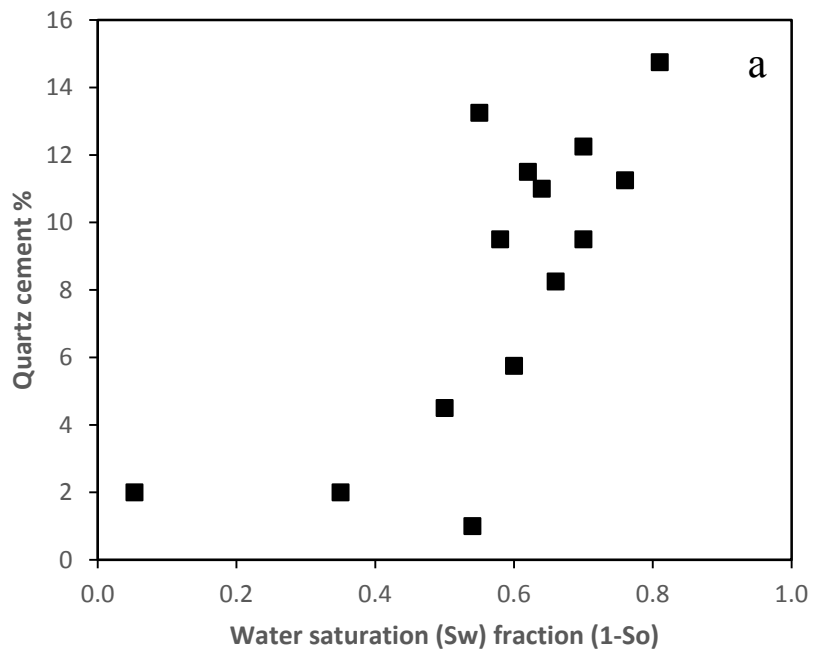


Figure 19

Parameters	Water saturation	Coarse grained sandstone facies - 1					Medium biotubated sandstone facies - 2					Very fine-fine biotubated sandstone facies - 3				
		MIN	AVERAGE	MAX	STDEV	NUM	MIN	AVERAGE	MAX	STDEV	NUM	MIN	AVERAGE	MAX	STDEV	NUM
Horizontal permeability (mD)	< 0.5	18.9	1117	2896	901	38	0.1	557	2424	520	99	0.6	25	249	36	152
	> 0.5	7.1	76	400	104.7	83	0.1	53	551	108	187	0.1	17	82	31	39
Core porosity %	< 0.5	13.2	19.3	24.2	2.5	38	3.1	20.2	27.0	3.6	99	8.9	19.1	24.0	2.2	152
	> 0.5	7.1	13.9	24.3	5.1	83	6.6	12.8	27.8	5.7	187	6.4	12.1	23.9	2.8	39
Quartz overgrowths %	< 0.5	2.0	4.8	11.0	3.0	8	1.7	5.9	15.2	3.5	17	0.0	1.5	12.0	3.2	16
	> 0.5	1.0	11.4	17.3	4.0	22	0.0	9.5	17.1	4.6	31	0.0	3.9	14.5	4.9	13
Detrital clay %	< 0.5	0.4	2.9	4.8	1.7	8	0.8	5.7	9.8	2.6	17	5.8	11.5	18.3	3.5	16
	> 0.5	0.0	4.6	11.8	3.9	22	1.7	5.9	13.0	3.1	31	6.0	11.5	23.2	4.9	13
Microcrystalline quartz %	< 0.5	0.0	1.3	7.3	2.5	8	0.0	0.2	1.8	0.5	17	0.0	5.9	12.0	3.4	16
	> 0.5	0.0	0.6	4.0	1.3	22	0.0	0.9	5.5	1.7	31	0.0	3.7	8.6	3.2	13
Total dolomite %	< 0.5	0.0	0.0	0.0	-	8	0.0	0.0	0.0	-	17	0.0	0.9	3.5	0.9	16
	> 0.5	0.0	0.0	0.0	-	22	0.0	0.0	0.0	-	31	0.0	0.2	1.4	0.2	13
Petrographic (visible) porosity %	< 0.5	12.7	15.5	20.0	2.6	8	6.1	14.4	20.3	3.40	17	6.0	11.8	16.3	3.4	16
	> 0.5	3.0	8.6	15.5	3.2	22	0.0	7.7	18.5	4.90	31	4.0	7.7	15.3	3.3	13
Intergranular volume %	< 0.5	20.3	26.6	29.5	3.6	8	25.5	29.1	36.1	2.70	17	24.8	33.3	44.5	4.5	16
	> 0.5	20.4	28.3	35.8	4.1	22	18.8	29.7	42.5	5.50	31	18.3	28.7	36.9	6.1	13

Well	7/12-A13	7/12-A8	7/12-A3	7/12-2
Depth TVD m	3667.90	3788.60	3675.50	3403.00
Part of figure 15 referred to	Fig. 15a	Fig. 15b	Fig. 15c	Fig. 15d
Lithofacies	Coarse grained graded facies	Medium-fine grained bioturbated facies	Coarse grained graded facies	Coarse grained graded facies
Water saturation %	88	70	62	5
Porosity %	11	13	20	20
Permability mD	3.65	7.06	332	1024
Quartz cement %	15	15	12	7

1 **The effect of oil emplacement on quartz cementation in a**
2 **deeply buried sandstone reservoir**

3

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5

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10

11 Key words: quartz cementation, quartz cement inhibition, diagenesis, oil charging, reservoir
12 quality

13

14 **Abstract**

15

16 Quartz ~~ement~~ is an important, porosity-occluding cement in sandstone reservoirs
17 that have been subjected to elevated temperature (>80 °-100 °C) for a substantial pe-
18 riod of time. The effect of oil emplacement on quartz cementation in reservoir sand-
19 stones is ~~controversial~~controversial; ~~with~~ some studies have ~~concluded~~ing that early
20 oil emplacement can inhibit quartz cementation leading to the preservation of poros-
21 ity, while other studies ~~claim~~have concluded that quartz cementation appears largely
22 unaffected by oil emplacement. Here we have studied shallow marine, Upper Juras-
23 sic sandstones from ~~the~~ Ula Field, Norwegian North Sea, with reservoir temperatures
24 ~~in the region~~ of approximately 150 °C, in order to determine whether oil emplace-

25 | ment had a significant ~~effect-impact~~ on diagenesis with particular attention to quartz
26 | cementation. Following sedimentological description of ~~the~~ cores, samples above and
27 | below the oil-water contact have been collected, adjacent to core analysis plug
28 | points. These samples then underwent a series of studies, including petrographic
29 | point counting with a transmitted light microscope, scanning electron microscopy
30 | (SEM), backscattered electron microscopy (BSEM), cathodoluminescence micros-
31 | copy (SEM-CL), and fluid inclusion studies. These data were integrated with routine
32 | core analysis and petrophysical log data. Density and resistivity log data have been
33 | used to determine the precise oil saturation of each sample studied. The distributions
34 | of all potential controls on porosity and permeability, such as grain size, sorting, ma-
35 | trix clay content, degree of bioturbation, the presence of grain ~~_~~coatings, and dolo-
36 | mite cement, as well as the amount of quartz cement, have been assessed. The pres-
37 | ence of primary oil inclusions within quartz cement shows ~~u~~ that oil ingress into the
38 | Ula reservoir commenced prior to the onset of quartz cementation. Very fine-
39 | grained, matrix-~~_~~rich, bioturbated and microquartz-~~_~~cemented sandstones have uni-
40 | formly low quartz cement contents irrespective of oil saturation. Medium-grained,
41 | graded, matrix-poor, microquartz-poor sandstones have quartz cement ranging from
42 | 1 % to greater than 17 %, associated with core porosities of about 22 % and 7 %, re-
43 | spectively. However, sandstones of the same facies (i.e. coarse and fine-to-medium
44 | grain size, and uniform low matrix clay content, similar depositional mineralogy and
45 | negligible grain coating materials) that have high oil saturations have significantly
46 | less quartz cement than equivalent samples with low oil saturations. Higher oil satu-
47 | rations equate to higher porosities and permeabilities in the medium-grained, graded,
48 | matrix-poor, microquartz-poor sandstones, coarser, matrix- and microquartz-poor
49 | facies thatwhich cannot be explained by any control other than the amount of quartz

50 cement as a function of pore fluid type. Oil emplacement therefore appears to have
51 inhibited quartz cementation at high oil saturations and can be viewed as a significant
52 control on reservoir quality. The significance of this study is that the presence of oil
53 in a sandstone reservoir, at the time that quartz cement was growing, can have a con-
54 siderable impact on reservoir quality. Models that seek to predict quartz cement and
55 reservoir quality in sandstones need to account for the timing of oil emplacement
56 compared to other diagenetic processes~~presence of oil on the amount of quartz ce-~~
57 ~~ment.~~

58

59

60 **Introduction**

61 The aim of this paper is to determine whether oil charge exerted a control on quartz
62 cementation, and consequently preserved porosity, in sandstones from the Upper
63 Jurassic ~~aged~~ Ula Formation in [Ula Field](#), Norwegian North Sea.

64

65 Understanding whether oil charge has stopped or retarded quartz cementation in the
66 Ula Formation could impact the prediction of porosity and permeability (reservoir
67 quality) distribution, leading to (i) increased accuracy in volumetric reserve
68 estimation (e.g. stock tank oil initially in place: STOIP) and (ii) being able to
69 forecast well performance pre-drill, allowing ~~the~~ wells with better delivery to be
70 drilled first. The accurate understanding and prediction of reservoir quality is
71 therefore key in order to obtain predictable well flow-rates throughout the lifetime of
72 a field/reservoir (Sneider, 1990). However, the prediction of reservoir quality is, and
73 will continue to be, a key challenge for petroleum exploration and reservoir
74 development. Defining and reducing risk associated with reservoir quality is

75 especially important in sandstone reservoirs that have been subjected to elevated
76 temperatures (typically taken to be >100 °C) because of quartz₂ and other deep burial-
77 related₂ cements (~~typically taken to be >100 °C~~), or high effective stress because of
78 compaction (Taylor et al., 2010).

79

80 Quartz~~cement~~ is volumetrically the most important cement in deeply buried
81 sandstones (Worden and Morad, 2000). ~~The Where quartz cement has been~~
82 ~~demonstrated to be the main control on reservoir quality, being~~ ability to predict
83 areas within reservoirs₂ or individual sandstone units₂ where quartz cement quantity
84 appears to be anomalously low could lead to ~~an~~ improved prediction of the
85 distribution of porosity and permeability in reservoirs where quartz cement has been
86 demonstrated to be the main control on reservoir quality. -The concept that oil
87 emplacement could inhibit quartz cementation and influence preservation of porosity
88 in sandstone reservoirs became known to many geologists from Johnson's (1920)
89 publication "The cementation process"₂ later developed in a series of papers
90 (Hawkins, 1978; Lowry, 1956; Scholle, 1977; Scholle and Halley, 1985). -However,
91 the question of the inhibiting effect of oil on mineral reactions in oil fields remains
92 open and is highly contentious (Sathar et al., 2012; Taylor et al., 2010).

93

94 All diagenetic reactions take place through an aqueous phase, by dissolution,
95 transport and re-precipitation (Worden and Morad, 2000). Hence, for diagenetic
96 reaction to occur there must be aqueous fluid ~~water present~~ to dissolve the mineral
97 grains, ~~an aqueous fluid~~ to transport dissolved material, and to facilitate ~~water at the~~
98 ~~site of~~ mineral precipitation. In an oil or gas field, displacement of the aqueous fluid
99 by hydrocarbons within the pore₂ space disrupts the pathway between the reactants

100 and sites of precipitation. As oil saturation increases (i) the residual (irreducible)
101 water becomes isolated within a continuous hydrocarbon phase, (ii) the aqueous
102 pathway becomes tortuous and diffusion rate decreases, or (iii) grain surfaces
103 become coated by oil if the sandstone is mixed- or oil-wet (Barclay and Worden,
104 2000a). As a consequence, most of those working on diagenesis and sandstone
105 reservoir quality assumed, up to the early-to-mid 1990s, that early oil emplacement
106 halted cementation and preserved porosity.

107

108 Many empirical studies from different basins and from reservoirs of different ages
109 have used, or discussed, the concept that early oil emplacement is a mechanism for
110 porosity preservation in sandstones (Bjørnseth and Gluyas, 1995; Dixon et al., 1989;
111 Emery et al., 1993; England et al., 2003; Gluyas and Cade, 1997; Gluyas et al., 1993;
112 Haszeldine et al., 2003; Higgs et al., 2007; Marchand et al., 2000; Marchand et al.,
113 2001; Marchand et al., 2002; Robinson and Gluyas, 1992; Saigal et al., 1992;
114 Wilkinson and Haszeldine, 2011; Wilkinson et al., 2004; Wilkinson et al., 2006).

115 These studies assumed that replacing formation water with oil simply stopped water-
116 mediated geochemical reactions. However, ~~in recent years~~, several other workers
117 have suggested that quartz cementation can continue unhindered even after oil
118 emplacement (Aase and Walderhaug, 2005; Bjørkum and Nadeau, 1998; Ehrenberg,
119 1990, 1993; Midtbø et al., 2000; Molenaar et al., 2008; Ramm and Bjorlykke, 1994).

120 To explain this rather different interpretation of diagenetic processes, it was assumed
121 that the combined diagenetic processes of dissolution-diffusion-precipitation utilise
122 residual water that clings to grain surfaces, and that this film of water apparently
123 permits mineral diagenesis to continue unhindered.

124

125 Comprehensive overviews of the empirical and theoretical arguments for and against
126 oil emplacement inhibiting quartz cementation (Worden and Morad, 2000; Worden
127 et al., 1998) concluded that the rate of quartz cementation that is synchronous with,
128 or after, oil emplacement in sandstone is probably reduced relative to rates of quartz
129 cementation in the underlying aquifer. These reviews concluded that quartz
130 cementation should be strongly inhibited if (i) the system has mixed wettability or is
131 oil-wet, (ii) the silica is externally supplied, (iii) the rate of diffusion is rate
132 controlling, or (iv) advection is an important part of the transport process. However,
133 even in internally-sourced silica systems with diffusion as the transport control, the
134 overall rate of quartz cementation should be inhibited due to added tortuosity
135 reducing the net rate of diffusion.

136

137 One of the main difficulties in definitively addressing the controversial question of
138 oil inhibition of quartz cement is the large number of potential controls on quartz
139 cementation, such as: (i) primary depositional factors (e.g. facies, grain size, sorting,
140 detrital mineralogy, matrix clay content), (ii) diagenetic factors (e.g. grain coating
141 clay and other minerals, pre-quartz, pore-filling cements, the source of silica), and
142 (iii) pore system characteristics (e.g. wettability and tortuosity). It is also important to
143 consider the oil-filling history of each facies. It is, therefore, possible that previous
144 studies have compared fundamentally different rocks, with different controls on
145 quartz cementation, when attempting to prove or disprove the effect of oil emplace-
146 ment on quartz cementation. In this study, we have taken samples with variable oil
147 and water saturations, as defined by wireline log data. We have been careful to only
148 compare sandstones from the same facies. We have also carefully quantified the
149 presence, type and extent of grain coating materials and taken account of pore-filling

150 | cements and only made comparisons between rocks that appear to be as similar as
151 | possible (apart from oil saturation). Key questions to be addressed are;

152

153 | 1. What was the timing of oil emplacement relative to quartz cementation in the
154 | Ula Formation?

155 | 2.1. How much quartz would be expected if no oil were present in the Ula
156 | Formation?

157 | 3.2. What other potential influences/controls are there on quartz cementa-
158 | tion in the Ula Formation?

159 | 4.3. Is there a difference in the quartz cement volume as a function of oil
160 | saturation for rocks that share similar pre-oil filling characteristics?

161 | 5.4. Can any differences in quartz cement volume be attributed to oil em-
162 | placement?

163

164 | **Geological background**

165

166 | [Ula Field](#) is an offshore oil [accumulation field](#) located in blocks 7/12 in the southern
167 | Norwegian sector of the North Sea (Fig. 1). Ula is located 280 km (149 miles) south-
168 | west of Stavanger at the eastern margin of the Central Graben along [the](#) Hydra Fault
169 | zone (Fig. 1) (Nedkvitne et al., 1993). In addition to [Ula Field](#), three other fields,
170 | Gyda, Tambar and Tambar East ~~fields~~, combine to make up the Ula-Gyda-Tambar
171 | (UGT) area (O'Connor et al., 2011). [Ula Field](#) was chosen to undertake this study
172 | due to the abundance of available core and supporting downhole data, which not only

173 gives good geographical coverage of the whole field but also gives good stratigraphic
174 coverage through the oil leg, transition zone and water leg.

175

176 | Ula Field consists of Mesozoic sediments in an anticlinal structure formed by late
177 Jurassic rifting and subsequent inversion in the Cretaceous and Tertiary (Brown et
178 | al., 1992). ~~Within the Ula field, t~~The main reservoir in the field is the Upper Jurassic
179 Ula Formation (Fig. 2) (Bergan et al., 1989; Karlsen et al., 1993; Partington et al.,
180 1993; Underhill, 1998). The Upper Jurassic Mandal Formation is considered to be
181 the source of the petroleum, beginning expulsion from the deeper parts of the Central
182 Graben during the late Cretaceous. Petroleum is still being generated in the UGT
183 area from the Mandal Formation source rock (Taylor et al., 1999). Within the UGT
184 area, the Mandal Formation also provides the seal for the underlying Jurassic sand-
185 | stones (Bjørnseth and Gluyas, 1995).-

186

187 The Upper Jurassic Ula Formation is a marine sandstone, up to 200m thick, that pro-
188 graded across Haugesund Formation outer-shelf mudstones following a sea level
189 | drop in the Kimmeridgian (Harris, 2006). ~~The Ula sandstonesFormation is are~~ typi-
190 cally very fine- to medium-grained (~~coarse grained in places~~), well-sorted, and lo-
191 cally can ~~locally~~ be glauconitic with some beds rich in shale fragments. ~~The Ula~~
192 Formation sandstones have been ~~was~~ described as arkosic (using the McBride, 1963,
193 classification scheme) and ~~was~~ were probably sourced from nearby Triassic sand-
194 stone outcrops (Gluyas, 1997). Much of tThe Ula Formation has been interpreted to
195 be intensively burrowed (Baniak et al., 2014; Baniak et al., 2015) and, even where no
196 burrows are evident, physical sedimentary structures ~~are nonetheless~~ can be absent,
197 suggesting that the unit has been intensively bioturbated. Facies subdivisions are

198 largely based on grain size and matrix content ; facies 1 is a normally-graded, me-
199 | dium ~~to coarse~~-grained [sandstone](#), with low detrital clay content, facies 2 is a biotur-
200 | bated [fine- to medium-grained](#) sandstone with variable detrital clay content, facies 3
201 | is a very fine to fine-grained sandstone that is intensively bioturbated with a high de-
202 | trital clay content. Trace fossils are ~~limited-dominated by~~ *Ophiomorpha*, suggest-
203 | ing a [high energy](#), shallow marine ([Skolithos ichnofacies](#)) origin for the sandstone
204 | (Baniak et al., 2015). The Ula Formation contains pervasively carbonate-cemented
205 | intervals that have negligible porosity and have been interpreted to result from bed-
206 | ded accumulation of shell debris followed by early diagenetic dissolution and reprecipitation as calcite cement (Gluyas, 1997). Core analysis porosity in the Ula Forma-
207 | tion typically lies between ~~14-7~~ and 28%. Permeability mostly falls between 650 to
208 | 850 mD for the better reservoir units (with extremes between 0.2 and 2800 mD)
209 | (Karlsen et al., 1993).

211

212 | The Ula Formation in [Ula Field](#) underwent more than 2000m of subsidence after the
213 | early Oligocene and is slightly overpressured, possibly as a result of the rapid late
214 | Tertiary subsidence (Fig. 3) (Harris, 2006; O'Connor et al., 2011). The Ula reservoir
215 | has been reported to have a slightly tilted oil-water contact (O'Connor et al., 2011).
216 | Reservoir temperature at 3,450 m (11,319 ft) is 143 to 145°C (Home, 1987).

217

218 **Methods and material**

219

220 One hundred and twenty two samples of conventional core plugs from four wells
221 | were obtained [for petrographic analysis](#) from the BP core store at Reslab laboratories
222 | in Stavanger, Norway ([Appendix 1](#)). These petrographic samples were taken directly

223 adjacent to plug points for conventional core analysis, thus ensuring that the petro-
224 graphic data tied to the core analysis data. Of the four wells, well 7/12-2 is in the oil
225 leg, and 7/12-A8 is in the water leg, 7/12-3A and 7/12-A13 traverse the oil and water
226 legs. The core sample suite covers the range of present subsurface depths between
227 about 3350 and 3850_m (10,991 and 12,631 ft) TVD, and spans the thickness of the
228 whole reservoir.

229

230 Samples were impregnated with blue resin and then made into polished thin sections.

231 Sandstone modal composition was obtained, in [the laboratories at Liverpool Univer-](#)
232 [sityhouse](#), by point counting all thin sections at 400 counts per section. Point count-
233 ing was performed using a x10 objective but higher power objectives were used
234 where necessary, e.g. for finer grained materials and grain coatings. The grid-spacing
235 was selected to ensure that the whole thin section was covered. Quartz cement was
236 differentiated from quartz grains by virtue of the presence of a trail of inclusions on
237 quartz grain surfaces. Grain sizes and grain coatings were determined for each sam-
238 ple using a Meiji 9000 microscope fitted with an Infinity 1.5 camera. Images were
239 collected and long axes of 100 grains per sample and were measured using Infinity
240 Analyser software, with the images and camera calibrated to standards of known
241 size. Fifty quartz grains per sample were measured, in [the laboratories at Liv-](#)
242 [erpool University](#), for the percentage of grain-coating microcrystalline quartz cover-
243 age (noting that negligible clay mineral coats were observed) of the freely-exposed
244 grain surfaces, using visual estimates compared to standard grain-coverage images.
245 Only potential sites for quartz cementation (i.e. facing pores, not coated with dead-oil
246 or with clay matrix) that were coated with microcrystalline quartz were measured
247 and expressed as a percentage of all potential sites for quartz cementation.

248

249 Scanning electron microscope (SEM) examination of all samples was undertaken
250 using a Philips XL 30 SEM with tungsten filament with an accelerating voltage of 20
251 kV, and 8 nA beam current for both secondary electron (SE) and backscattered elec-
252 tron microscopy (B)SEM. The SEM examination was carried out on polished sec-
253 tions and freshly fractured, stub-mounted samples coated with carbon and gold re-
254 spectively. Energy dispersive X-ray analysis (EDAX) provided qualitative composi-
255 tional analysis of clay minerals, carbonate cements and feldspars. Oil-stained sam-
256 ples were soaked in acetone to remove the oil stains which caused problems for the
257 vacuum system in the gold coater. The scanning electron microscope
258 cathodoluminescence (SEM-CL) images of quartz cemented grains were ~~collected to~~
259 ~~calibrate the light optics determined amounts of quartz cement. SEM-CL images~~
260 ~~were~~ collected at 10 kV by integrating the signals from 16 discrete frames using a
261 slow scanning raster; this took about 8 minutes for each image. The pPetrographi-
262 cally--defined quartz cement content was compared to the amount of quartz cement
263 discernible from SEM-CL images for three samples, one with high, one with inter-
264 mediate, and one with a low quartz cement content, to ensure that the point count de-
265 termination of quartz cementing was consistent.

266

267 Doubly polished fluid inclusion wafers for fluid inclusions microthermometric stud-
268 ies were selected to cover all facies from both the water leg and the oil leg and pre-
269 pared from core samples. An Olympus BX-60 petrographic microscope was used for
270 thermometry equipped with a Linkam THMSG 600 heating and cooling stage. This
271 enabled the measurement of the phase transition temperatures from -180 to 600 °C
272 with an accuracy of between ± 0.1 to ± 1.0 . Observations were made with different

273 magnifications (objectives 10x, 20x, 50x and 100x). Inclusions were photographed
274 with Digital Camera Olympus DP71 for the purpose of the fast mapping of inclusion
275 locations. Homogenisation temperature measurements were made on each inclusion
276 in each small piece of fluid inclusion wafer and then freezing point depression meas-
277 urements were made on each identified inclusion to prevent modification of the ho-
278 mogenisation temperature (Worden et al., 1995). Fluid inclusion samples were also
279 studied using a mercury UV source to differentiate oil inclusions from aqueous in-
280 clusions with a record being kept of the presence and absence (and relative abun-
281 dance) of petroleum inclusions.

282

283 Petrophysical and conventional core analysis data were made available by BP Nor-
284 way. ~~Core plugs were taken at 25 cm spacings with p~~Porosity and permeability were
285 measured for BP Norway using modern industry-standard methods and corrected for-
286 taking account of subsurface conditions confining stress. The permeability data re-
287 ported here were all collected from plugs drilled parallel to bedding (horizontal per-
288 meability). The provided data excluded any anomalous data from fractured plugs.

289 The plugs were collected using industry standard approaches at one every 25 cm
290 (9.84 inches), irrespective of be boundaries to ensure a representative petrophysical
291 dataset. The petrophysical log suites provided for this study were: caliper, bulk den-
292 sity, neutron porosity, sonic transit time, gamma ray, and shallow and deep resistiv-
293 ity. Porosity was calculated for each of the logs using the bulk density log (g/cm^3)
294 and the following relationship:

$$295 \quad \text{fractional porosity} = (\rho_{\text{mbd}} - \rho_{\text{amd}}) / (\rho_{\text{fd}} - \rho_{\text{amd}}) \quad (\text{eq 1})$$

296 Where:

297 ρ_{mbd} = measured bulk density for each sample (from petrophysical logs)

298 ρ_{amd} = average mineral density

299 ρ_{fd} = fluid density

300

301 The average mineral density employed was 2.66 g/cm³ (the density of quartz); this
302 average is reasonable since there is a proportion of feldspar with lower density and a
303 proportion of carbonate minerals with higher density. The average fluid density was
304 assumed to be 1.00 g/cm³.

305

306 Water saturation was calculated from the petrophysical log data for each 10 cm
307 depth-interval using the Archie equation. Hole conditions were not an issue in the
308 studied section because it did not include poorly-lithified or soluble sections such as
309 mudstones or evaporites. Values of n, a, and m were fixed at 2.0, 0.81 and 2.0, re-
310 spectively, as used by the field operators, following industry standard methods and
311 calibration. Deep induction resistivity log data were used since these give true forma-
312 tion resistivity, unaffected by invasion of the formation by drilling fluids (Asquith
313 and Gibson, 1982). The reported formation water resistivity for ~~the Ula Field~~[Ula](#)
314 [Field](#) is 0.025 ohm.m (Oxtoby, 1994).

315

316 **Results**

317 ***Wireline and core analysis data***

318 The calculated density log porosity values correlate well with the core analysis po-
319 rosity values suggesting that the ([wireline](#)) density log porosity values are credible
320 (Fig. 4). The density log-derived porosity and water saturation values for each well
321 are illustrated in Figure 5. The log-derived porosity of the four wells seems to be

322 highest at the shallowest positions with porosity routinely > 20% at the crest of the
323 field but no higher than 10-15 % at the flanks of the field (Fig. 5). The wells included
324 in this study show a wide variation in water saturations; well 7/12-2 has low water
325 saturation, wells 7/12-A13 and 7/12-A08 have high water saturation. Well 7/12-3A
326 has low to intermediate water saturation. The very low porosity and high water satu-
327 ration spikes (e.g. for well 7/12-2) represent pervasively calcite cemented intervals.

328

329 The core analysis data have been split between the three main facies as determined
330 by sedimentological facies description of the core and then further split by the wire-
331 line-calculated water saturations (~~see~~ Fig. 5). Porosity-permeability data for each
332 facies, split by water saturation, are displayed in Figure 6 showing that samples with
333 lowest water saturations, especially from facies 1 and facies 2, have the highest po-
334 rosity and permeability values.

335

336 *Facies and detrital minerals*

337 The ~~new~~ point count data confirm that the Ula Formation reservoir is an arkosic
338 sandstone (Fig. 7). The wells used in this study and different facies within the core
339 are not differentiated on the ternary QFL diagram since the data lie in one cluster.

340 The main variations in different facies are in terms of: grain size, clay content and
341 degree of bioturbation. A full listing of petrographic data is given in Appendix 1.

342

343 Facies 1 is medium-~~to coarse~~-grained, moderately well-sorted (0.52 ϕ), with low de-
344 trital clay content (mean 4.2 %, Table 1) and no direct sign of bioturbation. Facies 1
345 tends to be in upward-fining (i.e. graded) beds that are devoid of small-scale sedi-
346 mentary structures. Point counting results show that the most dominant detrital min-

347 | eral ~~in facies 1~~ is monocrystalline quartz (mean 34 %), followed by K-feldspar (mean
348 | 11 %) and plagioclase (14 %). Polycrystalline quartz and traces of rock fragments are
349 | also present in this facies.

350

351 | Facies 2 is a fine- to medium-~~grained~~ sandstone that is moderately- to well-sorted
352 | (0.62 ϕ), with a variable detrital clay content ranging from 0.8 to 13.0 % (mean 6.5
353 | %) (Table 1). Facies 2 is bioturbated with no remaining primary sedimentary struc-
354 | tures due to bioturbation with cm-scale horizontal burrows, identified as *Ophiomor-*
355 | *pha* or *Palaeophycus*. The dominant detrital mineral grains in facies 2 are monocrys-
356 | talline quartz (mean 28 %), K-feldspar (mean 9 %), plagioclase (mean 15%) and rock
357 | fragments (<3 %).

358

359 | Facies 3 is a very fine- to fine-grained sandstone that is moderately-sorted (0.83 ϕ)
360 | with a high detrital clay content, based on point-count data ranging from 5.7 to 23.2
361 | % (mean 11.5 %) (Table 1). Facies 3 is intensively bioturbated with vertical and
362 | horizontal burrows identified as *Teichichnus* or *Rhizocorallian*. The dominant detri-
363 | tal mineral grains in facies 3 are monocrystalline quartz (mean 27 %), K-feldspar
364 | (mean 7 %), and plagioclase (mean 11 %). This facies has localised accumulations of
365 | stratigraphically-localized shell fragments and only a small amount of rock frag-
366 | ments.

367

368 | Detrital clays are present as mm- to cm-sized patches and thin discontinuous layers.
369 | Detrital clay and is most abundant in the very fine to fine-grained bioturbated fa-
370 | cie units. The highest clay contents (of u Up to 26 % detrital clay is) are found in the
371 | very fine- to fine-grained, highly bioturbated facies and the lowest clay of <1 % are

372 found in the ~~medium~~~~coarse~~-grained, graded sandstones ~~with no~~~~evidence of~~ evidence of
373 bioturbation. ~~From the~~ SEM observations indicate that the ~~clay mineralogy of the de-~~
374 trital clay matrix is dominated by illite and chlorite, ~~as shown~~confirmed by XRD
375 analysis (trace not illustrated in this paper).

376

377 ***Overall paragenesis***

378 A summary paragenetic sequence is presented in Figure 8, with supporting
379 photomicrographs and SEM images in Figures 9, ~~10 to~~, 11 ~~and 13~~. The sequence is
380 subdivided into ‘early’ and ‘late’ diagenesis. Early diagenetic events took place in
381 depositional pore waters, ~~and their evolving derivatives~~, at relatively shallow depths,
382 with an influence of depositional and influxing meteoric water (Morad et al., 2010),
383 whereas ~~subsequent~~‘late’ diagenesis during burial occurred after the main phase of
384 ~~burial related~~ compaction and is characterised by growth at higher temperatures.

385

386 **Early diagenesis**

387 Early diagenesis commenced with admixing and infiltration of detrital clay into the
388 newly deposited sediment, largely due to bioturbation. This resulted in patchy
389 distribution of detrital clays and created locally cleaner pathways that potentially
390 promoted later throughput of diagenetic fluids. This was accompanied by initial
391 compactional porosity-loss, mainly through the reorganisation of grains and
392 mechanical compaction into a stable framework. Framboidal pyrite (Fig. 9a) is
393 associated with detrital clay and precipitated in a reducing environment at relatively
394 shallow depth, during the decay of organic fragments by sulphate-reducing bacteria
395 (Burley & Worden, 2003). Some beds are completely cemented with early diagenetic
396 calcite and have negligible porosity. Dissolution of stratigraphically-restricted shelly

397 carbonate fragments, and the growth of locally pervasive minor non-ferroan calcite
398 within primary pores, occurred during early diagenesis. This led to total occlusion of
399 porosity (see later section on wireline log analysis). Some beds are thus completely
400 cemented with early diagenetic calcite and have negligible porosity. These nodular or
401 bedded early calcite-cemented samples have been excluded from further data
402 analysis (i.e. no point count data for samples with pervasive calcite cement included
403 in Appendix 1) since they do not inform the discussion about the effect of oil
404 emplacement on burial diagenesis (quartz cementation).

405

406 Bacterial sulphate reduction, responsible for framboidal pyrite growth (Fig. 9a), led
407 to acidification, which resulted in minor dissolution of unstable grains and created
408 minor amounts of secondary porosity (Fig. 9b). These minor, partially-dissolved
409 grains were typically replaced by small quantities of patchy, early diagenetic chlorite
410 (Fig. 9c). Chlorite predominantly occurs as minor pore-filling rosettes.
411 Volumetrically, pore-filling chlorite is present in small quantities (typically < 1 %).
412 Chlorite appears to be facies-related with the majority occurring in the very fine- to
413 fine-grained, matrix rich, bioturbated facies 3. Grain-coating chlorite is not present
414 in the studied Ula Formation reservoir sandstones.

415

416 Microcrystalline quartz locally coats grains (Fig. 9d). By reference to evidence from
417 equivalent Upper Jurassic outcrops at Brora, on the NE coast of Scotland, UK, ÷ the
418 microcrystalline quartz (dealt with in detail in a subsequent section) was probably
419 sourced from the dissolution of unstable siliceous bioclasts (e.g. sponge spicules), at
420 shallow burial depths (< 60 °C) (Vagle et al., 1994).

421

422 ~~Dissolution of stratigraphically restricted shelly carbonate fragments, and the growth~~
423 ~~of locally pervasive minor non-ferroan calcite within primary pores, occurred during~~
424 ~~early diagenesis. This led to total occlusion of porosity (see later section on wireline~~
425 ~~log analysis). Some beds are thus completely cemented with early diagenetic calcite~~
426 ~~and have negligible porosity. These nodular or bedded early calcite cemented~~
427 ~~samples have been excluded from further data analysis (i.e. no point count data~~
428 ~~included in Appendix 1) since they do not inform the discussion about the effect of~~
429 ~~oil emplacement on burial diagenesis (quartz cementation).~~ Further dissolution of
430 feldspar (Fig. 9e) seems to have resulted in the precipitation of a small quantity of
431 early (i.e. pre-compactional) quartz overgrowths, present within quartz-quartz grain
432 contact zones (Figs. 9e-f). Early diagenesis terminated with the end of the main
433 phase of burial-related compaction, which is generally assessed as moderate to strong
434 as evidenced by the prevalence of long and sutured grain contacts.

435

436 **Late diagenesis**

437 Minor feldspar dissolution continued beyond the main phase of compaction, as
438 indicated by locally significant, but volumetrically-minor, secondary pores that have
439 no evidence of compaction. This phase of grain dissolution liberated Al and Si and
440 ~~potentially contributed to~~resulted in the precipitation of the diagenetically-dominant,
441 post-compactional quartz overgrowths (Table 1; ~~the focus of the next section~~) and
442 minor quantities of clay minerals (Fig. 9e) (Barclay and Worden, 2000b). The switch
443 from feldspar dissolution to feldspar growth (Worden and Rushton, 1992), required
444 ~~There must have been~~ a switch from cation-poor and/or feldspar-dissolving (low pH
445) to cation rich and/or (moderate pH) pore-waters ~~that resulted in the precipitation of~~
446 minor feldspar overgrowths (Fig. 9e). This change also and led to local growth of

447 | minor quantities of dawsonite (sodium aluminum hydroxycarbonate) within primary
448 | pores (Worden, 2006) ~~within primary pores~~. Minor quantities of late illite
449 | precipitated, locally coating quartz overgrowths at this late stage (Fig. 9d).

450

451 | Non ferroan and ferroan dolomite cement are present in the Ula Formation (Ula
452 | field), with the most volumetrically-important being rhombic ferroan dolomite (Fig.
453 | 10a). The mean point count volume for total dolomite is ~0.7 %, (Table 1). Ferroan
454 | and non-ferroan dolomite are only present in very fine to fine bioturbated sandstones
455 | with abundant matrix (facies 3; Table 1). The ferroan dolomite replaces and locally
456 | crosscuts quartz cement and ~~thus so seems to have~~ formed after quartz cement. ~~The~~
457 | ~~h~~Hydrocarbon influx start~~seems to have occurred~~ after the start-onset of the main
458 | phase of quartz cement growth since residual hydrocarbon is present on quartz
459 | cement surfaces (Fig. 10b).

460

461 | ***Quartz diagenesis***

462 | Both grain-coating microcrystalline quartz and quartz overgrowths are present in the
463 | Ula Formation ~~are~~.

464

465 | The Ula ~~Formation sandstones~~ have variable amounts of quartz overgrowth cement
466 | ranging from high porosity sandstones with relatively small amounts of quartz ce-
467 | ment (i.e. a few percent quartz cement) (Figs. 10a, b and c) to pervasively quartz-
468 | cemented samples in which the porosity is almost totally occluded (Figs. 10, d, e and
469 | f). Quartz overgrowths are not visibly zoned when studied using SEM-CL (Figs. 10e
470 | and f). ~~SEM-CL confirms the volumetric importance of quartz cement in the Ula~~

471 | ~~Formation.~~The euhedral edges of quartz overgrowths are locally stained by dead oil
472 | or bitumen (Fig. 10b). However, some low porosity sandstones in the finest grained
473 | and most clay-rich facies 3 have little quartz cement due to other pore-filling materi-
474 | als such as abundant pore-filling clay and localised Fe-dolomite (Fig. 10a, Table 1).
475 | Quartz overgrowths are euhedral when facing open pores (Figs. 10b, c and e). The
476 | boundaries between detrital quartz grains and quartz overgrowths are typically char-
477 | acterized by a dust rim composed of fine-grained clay minerals or fluid inclusions
478 | (Figs. 10b, c and d). Quartz overgrowths can range in thickness from < 10 μm to >
479 | 50 μm. At sites where overgrowths from neighbouring grains interlock, porosity
480 | tends to be locally fully occluded. Quartz overgrowths are least abundant in facies
481 | type 3 but facies 1 and 2 have highly variable quantities of quartz overgrowths (Ta-
482 | ble 1).

483

484 | The quartz cement-poor, medium-grained graded samples from low water saturation
485 | samples from 7/12-2 notably have relatively clean, largely unmodified (i.e. as-
486 | deposited) detrital quartz grain surfaces (Fig. 11). Such grains are marked by a lack
487 | of microquartz cement coatings and no more than nascent, patchy and very thin
488 | quartz overgrowths (Figs. 11b and d). These clean quartz grains from the oil leg have
489 | subtly uneven surfaces that resemble detrital grains from modern environments.

490

491 | Quartz cement seems to increase in overall abundance with increasing depth for the
492 | medium-grained graded facies 1 (Fig. 12). -The same pattern of increasing quartz
493 | cement with depth can be discerned for the fine- to medium--grained bioturbated fa-
494 | cies 2 but there is no pattern for the relatively quartz cement-poor very fine to fine-
495 | grained bioturbated facies 3 (Fig. 12)

496

497 Light optics revealed a very fine-grained, colourless mineral coating with low to in-
498 termediate birefringence in some samples (Fig. 13a); SEM observation confirmed
499 that this is microcrystalline quartz (Fig. 13b, Table 1). The quantity of microquartz is
500 greatest in the very fine- to fine-grained bioturbated facies 3, with much less in the
501 fine- to medium-grained and bioturbated facies 2 and medium-grained graded and
502 coarse facies 1 and 2 (Figs. 12 and 14a, Table 1). There is no systematic pattern of
503 microquartz variation with depth of burial (Fig. 12). Some samples have unusually
504 large amounts of microquartz, others have low to negligible amounts. The micro-
505 quartz crystals tend to be < 5 µm in size and vary in shape from anhedral (typically
506 rounded) to euhedral. Microquartz tends to sit on detrital grain surfaces but locally
507 forms thick irregular coatings that extend into neighbouring pores and pore-filling
508 patches. Microcrystalline quartz cement appears to be dominant only in facies 3
509 (very fine to fine bioturbated sandstone with abundant matrix) but it is typically pre-
510 sent in small amounts in the coarser facies although one or two samples from the the
511 medium-grained graded facies 1 and fine- to medium-grained bioturbated facies 2
512 medium and coarse facies contain several percent microquartz. These Facies 3 sam-
513 ples tend to have commensurately smaller amounts of quartz cement than the micro-
514 quartz-poor medium-grained graded facies 1 and fine- to medium-grained biotur-
515 bated facies 2 that have little microquartz (Table 1; Fig. 14a). As well as point count-
516 ing microquartz, the percentage of detrital quartz grains that are coated with micro-
517 crystalline quartz was determined by visually estimating 50 grains per section for a
518 subset of the samples (Fig. 14b). Medium-grained graded facies 1 sandstones have
519 grains that are, on average, about 10 to 20% coated with microquartz and have low
520 overall point counted quantities of microquartz (Figs. 14a and b). Very fine- to fine-

521 | grained bioturbated facies 3 [sandstones](#) contains some grains that are approaching
522 | 100% grain coating with microquartz. [Fine- to medium-grained bioturbated](#) facies 2
523 | sandstones tend to have intermediate degrees of grain coating by microquartz (Fig.
524 | 14b).

525

526 ***Fluid inclusion Analysis***

527 | Samples for fluid inclusion study were selected from both oil and water legs. Ho-
528 | mogenization temperatures were measured for aqueous inclusions and petroleum in-
529 | clusions in 12 samples in wells 7/12-2, 7/12-A3, 7/12-5, 7/12-A08, and 7/12-A13 of
530 | the Ula Formation. Primary fluid inclusions that fluoresced under UV illumination
531 | are present in quartz overgrowths (Fig. 15) showing that some oil was present during
532 | the growth of quartz. Non-fluorescent primary aqueous fluid inclusions are also pre-
533 | sent in quartz overgrowths. Petroleum inclusions are generally larger in size (Fig.
534 | 15a-d) and have a higher vapour-liquid ratio than aqueous inclusions and were there-
535 | fore easier to work with. Aqueous inclusions range in diameter from 1 to 17 μm . Pe-
536 | troleum inclusions range in diameter from 7 to 38 μm . The liquid to vapor ratio for
537 | aqueous fluid inclusion was consistently about 8:1 and for petroleum inclusion was
538 | about 5:1. All the homogenisation temperatures recorded here are from inclusions
539 | within quartz overgrowths or [sitting-located](#) between detrital quartz grains and their
540 | quartz overgrowths. Only homogenization temperatures that were reproducible
541 | within (<5 °C) were recorded. All inclusions homogenised to liquid upon heating.
542 | Aqueous inclusion populations tend to [be](#) unimodal between 120 and 174 °C with the
543 | lowest recorded aqueous inclusion homogenization temperature being 103 °C. Petro-
544 | leum inclusions homogenized between about 80 and 142 °C. Pressure corrections

545 were not made to the aqueous inclusion homogenisation temperatures because the
546 formation water was probably saturated with methane at the time of trapping (Hanor,
547 1980), implying that the measured homogenisation temperatures are representative of
548 the actual trapping temperature for the aqueous inclusions. Homogenisation tempera-
549 tures of inclusions trapped in quartz are not likely to have been re-equilibrated and so
550 represent the true trapping temperature (Worden et al., 1995). The oil inclusions can-
551 not easily be used to reveal the conditions of trapping since the precise PVT proper-
552 ties of the trapped petroleum are not known.

553

554 Histograms of homogenization temperatures four representative samples are given in
555 Figure 16 and summarized in Table 2. The present-day formation temperature for
556 well 7/12-A3 is 154°C (determined from drill stem testing) which compares favora-
557 bly with the homogenisation temperatures (Fig. 16) although the modal fluid inclu-
558 sion homogenization temperature is lower than the present day temperature.

559

560 **Discussion**

561 *Quartz cementation in the presence of oil*

562 The presence of primary oil inclusions in quartz cement indicates that some oil was
563 present in the reservoir when this authigenic mineral was being precipitated. The
564 very lowest homogenisation temperatures for the aqueous inclusions is 103°C, al-
565 though a more typical minimum homogenisation temperatures for the aqueous inclu-
566 sions is 120°C (Fig. 16) which is somewhat higher than the threshold of 80°C widely
567 assumed to be the temperature above which quartz cement grows (Walderhaug,
568 1996). The oil saturation at the time of the growth of quartz cement, and thus inclu-

569 sion trapping, is not known although it is noteworthy that the fluid inclusion sample
570 with highest oil saturation at the present day (7/12-2, 3403.00m) has the lowest per-
571 centage of quartz cement (Table 2) and was visually estimated to have a relatively
572 great abundance of petroleum inclusions (Fig. 15). Having some oil in the pore net-
573 work clearly does not automatically preclude quartz cementation.

574

575 *Quartz cement modeling in the presence of oil*

576 | ~~In recent years~~ Simple modeling approaches have been developed to try to link
577 | quartz cement abundance with burial and thermal histories (Bjørkum et al., 1998;
578 | Lander and Walderhaug, 1999; Walderhaug, 1990, 1994a, b, 1996; Walderhaug et
579 | al., 2000). These ~~fundamental~~ models were calibrated by examining quartz cement
580 | quantities in different sandstones from one basin (Norwegian North Sea) and relating
581 | ~~these quantities~~ to the burial history of each sandstone reservoir in the calibration
582 | dataset. All of these models assumed that quartz cement is internally-derived and that
583 | the main control is the rate of quartz precipitation. The timing of quartz cementation
584 | in each well was derived by using aqueous fluid inclusion temperatures from the
585 | sandstones in the calibration dataset and the assumption that quartz cementation was
586 | continuous from the lowest recorded aqueous inclusion homogenization temperature
587 | onwards (despite there being punctuated fluid inclusion records reported)
588 | (Walderhaug, 1994a). Geometric characteristics were accounted for by examining
589 | grain size (and relating this to available surface area) and the fraction of grains that
590 | are quartz (as opposed to feldspars, lithics, etc.). The published models were thus cal-
591 | ibrated using a number of basic assumptions. Interestingly, the models were also cal-
592 | ibrated ~~utilising the fundamental~~ assumption~~ing~~ that emplacement of oil did not in-

hibit quartz cementation. Since the published ~~The~~ models (Walderhaug, 1990, 1994a, b, 1996; Walderhaug et al., 2000) involved the assumption that oil had no effect on quartz cement growth. ~~they~~ These models therefore seem to be fundamentally unsuitable for attempting to modeling any effect of oil emplacement on quartz cementation. However, for medium-grained graded facies 1 and fine- to medium-grained bioturbated facies 2 in the oil leg of Ula oil field, the relative quantity of quartz cement and the elevated porosity look anomalous compared to the quantities found in the water leg (Table 1, Fig. 12). There are a finite number of controls on anomalously high porosity-low quartz cemented sandstones (Bloch et al., 2002); these possible controls will now be examined.

603

604 ***Main controls on porosity-loss above and below the oil-water contact***

605 A comparison of the effects of cementation and compaction using a plot of pore-
606 filling cement versus intergranular volume (also known as a Houseknecht-type plot)
607 based on petrographic data (Fig. 17) shows that there is a difference in what process
608 has controlled porosity-loss as a function of position in the oil field. On average, the
609 oil leg samples occupy a central position in the diagram showing a combination of
610 compaction and cementation leading to the final porosity. In contrast the oil-water
611 leg samples sit mainly within the cementation field. The main cement is quartz so
612 that it could be concluded that quartz cement dominates in the high water saturation
613 zone while there has been less cement in the high oil saturation zones (Fig. 17). In
614 contrast, it could also be concluded that compaction has been relatively more impor-
615 tant than cementation in the oil leg than compared to the water leg so that there is a

616 need to compare cement volumes for initially similar samples (same facies) between
617 the oil and water legs.

618

619 ***Grain size, detrital clay and grain-coating microcrystalline quartz and***
620 ***quartz cementation***

621 Grain size is broadly uniform within each facies so that this cannot be invoked as the
622 primary cause of variable amounts of quartz cement in the various facies -(Table 1,
623 Appendix 1). Similarly, both fine- to medium-grained bioturbated and medium-
624 grained graded sandstone samples each have approximately consistent quantities of
625 detrital matrix clay, so this, too, can be excluded as a control on quartz cement within
626 each facies (Fig. 12; Table 1). It is noteworthy that very fine to fine bioturbated
627 facies 3 has a far higher quantity of matrix clay than medium and coarse facies 1 and
628 2. However, for the water leg samples from the three facies, there is a well-
629 developed, inverse correlation between the amount of detrital clay and the amount of
630 quartz cement (Table 1). This suggests that the more argillaceous-rich, finer-grained,
631 heavily bioturbated samples have experienced inhibition of quartz cement compared
632 to the cleaner medium- and coarse-grained sandstones. Ferroan dolomite is not a
633 major mineral cement but it too correlates with primary facies and detrital clay
634 content possibly (Table 1).

635

636 Microquartz is an abundant, and pervasively grain-coating, of cement found on
637 detrital quartz grains ~~by microquartz is prevalent,~~ in the very fine- to fine-grained
638 bioturbated facies 3 (Fig. 14). Quartz cementation appears to have been inhibited by
639 microquartz coats irrespective of pore fluid type (Fig. 12; Table 1). This effect has

640 | ~~previously~~ been reported previously (Aase et al., 1996; French and Worden, 2013;
641 | French et al., 2010; French et al., 2012; Hendry and Trewin, 1995; Ramm et al.,
642 | 1997; Weibel et al., 2010; Worden et al., 2012). It is ~~noteworthy~~significant that a
643 | small subset of fine- to medium-grained bioturbated facies 2 samples contain
644 | measurable microquartz (Fig. 14a). These samples have commensurately reduced
645 | amounts of quartz cement and elevated porosity. For example, samples of fine- to
646 | medium-grained bioturbated facies 2 in well 7/12-3A at 3,559-3,566 m (11,677-
647 | 11,699 ft) TVDss contain a few percent microquartz (Fig. 12) and have anomalously
648 | elevated porosity as a consequence of the inhibition of quartz cement (Figs. 5 and
649 | 12).

650

651 | When grain-coating microquartz percentage, and ~~degree~~percentage of surface area
652 | of grain-coating by microquartz, are plotted against quartz cement (Fig. 14a), it is
653 | apparent that samples from medium-grained graded facies 1 (and fine- to medium-
654 | grained bioturbated facies 2) show a large range of quartz cement volumes
655 | irrespective of the amount of microquartz. Although microquartz exerts a control on
656 | the development of quartz overgrowths, it is not particularly abundant in medium-
657 | grained graded facies 1 or fine- to medium-grained bioturbated facies 2 and it cannot
658 | explain the full range of abundance of quartz cement. This suggests that there is an
659 | additional control, other than microquartz, that has determineding the amount of
660 | quartz cement in facies 1 and 2.

661

662 | Since grain-coating microquartz is only observed in large amounts in very fine- to
663 | fine-grained bioturbated facies 3, it seems likely that this is the only facies in which
664 | there was an abundant potential source for the microquartz. Microquartz in Upper

665 Jurassic sandstones from the North Sea is typically attributed to detrital sponge
666 spicules (Aase et al., 1996; Vagle et al., 1994). Based on the literature-based
667 interpretation that the microquartz was sourced from replaced sponge spicule
668 fragments, it can thus be inferred that detrital fragments of sponge spicules were
669 preferentially concentrated in the finest-grained sand fraction. We here speculate
670 that the grading of the silica bioclasts into the finest sand fraction may be a
671 consequence of their fragility and consequent attritional diminution during transport
672 from their original location on the marine shelf. While these silica bioclasts have
673 successfully led to the inhibited- of quartz cement (good for reservoir quality),
674 they are found in the finest sandstones (facies 3) that also contain abundant matrix
675 clay so that the reservoir quality has been detrimentally controlled by other factors.

676

677 ***Quantity of quartz cement above and below the oil-water contact for***
678 ***rocks of the same pre-oil filling characteristics?***

679 The characteristics of the three different primary facies above and below the oil-
680 water contact (and in the transition zone) are summarized in Table 1. The three facies
681 have been defined by grain size, matrix clay content and sedimentary structures (in-
682 cluding grading and degree of bioturbation) and so have self-consistent grain size
683 and sorting characteristics and detrital mineralogy (Fig. 7). They also have consistent
684 quantities of detrital clay and grain-coating microcrystalline quartz (Table 1). Sam-
685 ples that have been fully cemented with early diagenetic calcite, i.e. with all pore
686 space filled very soon after deposition, have been removed from the analysis since
687 they cannot record the effects of oil emplacement of burial diagenetic processes. The
688 amounts of ferroan dolomite observed in pores are approximately consistent for the

689 different facies (Table 1). The quantity of petrographically-defined quartz cement has
690 been plotted against specific water saturation for each sample, derived using log data
691 with the data split by the petrographically-defined microquartz content (Fig. 18).
692 This approach shows that low water saturations (and therefore high oil saturations)
693 equate to less quartz cement in medium-grained graded facies 1 (Fig. 18a) and fine-
694 to medium-grained bioturbated facies 2 (Fig. 18b), relative to samples of these same
695 facies from the water₋leg. ~~Medium and coarse grained samples with relatively high~~
696 ~~water saturation also tend to have reduced amounts of quartz cement for increasing~~
697 ~~quantities of microquartz (Fig. 18).~~ There does not appear to be a simple relationship
698 between water saturation and quartz cement content for very fine to fine bioturbated
699 facies 3 (Fig. 18c) although large quantities of microquartz in this facies equate to
700 negligible amounts of quartz cement in all cases. The lack of correlation of water
701 saturation with quartz cement for the very fine to fine bioturbated facies may be a
702 result of: (1) the large quantity of pre-existing detrital clay that left less room for
703 quartz cement to grow (Fig. 12; Table 1), or (2) the great abundance of grain-coating
704 microquartz that prevented quartz cement precipitating (Figs. 12, ~~and~~ 14, 18c; Table
705 21).

707 Focusing on the medium-grained graded facies 1 sandstones that have less than 20%
708 grain coating, it is possible to discern a good correlation between water saturation
709 and quartz cement content (Fig. 19a). There are good inverse relationships between
710 water saturation and core analysis porosity and permeability (Figs. 19b-c). There is
711 also a good inverse relationship between quartz cement and core analysis porosity
712 (Fig. 19d) confirming that quartz cement is the master control on reservoir quality.

713

714 The conclusion from the data detailed in Table 1 and Figures 18 and 19 is that for
715 medium-grained graded facies 1 sandstones, that have virtually identical and small
716 amounts of detrital clay, ferroan dolomite, and grain-coating microquartz, samples
717 from the oil leg appear to have less quartz cement, higher porosity and higher perme-
718 ability than samples from the water leg. The same is broadly true for fine- to medi-
719 um-grained bioturbated facies 2 sandstones (Table 1) but very fine to fine
720 bioturbated facies 3 samples tend to have a relatively small quantity of quartz cement
721 irrespective of oil saturation. Facies 3 sandstones have smaller quantities of quartz
722 cement than facies 1 and 2 due to the combined effects of grain coating microquartz
723 (Fig. 14) and relatively minor extra amounts of ferroan dolomite and abundant matrix
724 clay (Table 1).

725

726 The assessment of the effects of compaction versus cementation (Fig. 17) shows that
727 water leg samples tend to be more cementation-dominated than oil leg samples. For
728 samples of the same facies, with the same microquartz content, this difference is the
729 result of there being more quartz cement in the water leg than the oil leg (Fig. 18a).
730 We can thus surmise that the growth of quartz cement in the oil leg has been inhibit-
731 ed relative to growth in the water leg. It seems likely that this difference is the result
732 of prolonged (or more intense) quartz cementation in the water leg resulting in more
733 quartz cement relative to the oil leg.

734

735 ***Synthesis: has oil slowed quartz cementation and therefore caused***
736 ***preservation of porosity?***

737 The key question addressed by this study is whether emplacement of oil during
738 diagenesis led to inhibition of quartz cementation in the Ula Formation in [Ula Field](#).
739 ~~When compared, s~~ Samples ~~for similar facies~~ from the oil leg have higher porosities
740 and less quartz cement than comparable samples from the water leg for facies 1 and
741 facies 2 (Table 1, Fig. 18). This difference cannot be explained by demonstrable var-
742 iances in abundance of microcrystalline quartz coatings (Figs. 12 and 14), grain size,
743 grain-coating chlorite or the presence of other subordinate pore-filling cements (Ta-
744 ble 1). We therefore propose that the differences in porosity and quartz cement abun-
745 dance as a function of oil saturation may be directly attributed to differences in the
746 dominant fluid type within the pore ~~-~~space of these samples.

747

748 In essence, the rate of quartz cement growth will be limited to the slowest step in the
749 sequence of steps: supply, transport and precipitation. Having oil present in the pore
750 space during quartz cementation (as shown by oil inclusions in quartz cement; Figs.
751 15, 16) may have caused the rate of quartz *precipitation* to slow significantly relative
752 to similar samples with high water saturation and therefore led to less quartz cement
753 being precipitated. However, the recorded reduced abundance of quartz cement in the
754 oil leg samples (in [medium-grained graded](#) facies 1 and [fine- to medium-grained](#)
755 [bioturbated](#) 2) could also be the result of reduced rates of silica *supply* in the oil leg
756 (presumably from internal, stylolite-related, sources). Alternatively, there may have
757 been reduced rates of silica *transport* in the presence of oil due either to slowed ad-
758 vection (resulting from relative permeability effects) or slowed diffusion (resulting
759 from tortuosity effects) (Worden et al., 1998). [The lack of correlation between IGV](#)

760 and quartz cement content (Table 1, Appendix 1) could be used to infer that pressure
761 solution (chemical compaction) has not been affected by the emplacement of oil if
762 we assume that quartz cement was only supplied by local, intra-facies pressure solu-
763 tion. However we cannot be sure that quartz cement in facies 1 and 2 sandstones has
764 not been supplied by feldspar-clay reactions (Barclay and Worden, 2000b), pressure
765 solution in surrounding mudstones (Land and Millken, 2000) or clay-rich sandstones
766 (Trewin and Fallick, 2000), export of biogenic silica from finer sandstone facies (e.g.
767 facies 3) (Worden and Morad, 2000) or even mass flux from deeper in the basin
768 (Giles et al., 2000). Although we cannot be sure which of supply, transport and pre-
769 cipitation rate has been slowed by the presence of oil we can state that the overall
770 process of quartz cementation has been significantly slowed in cleaner, less fine-
771 grained, minimally microquartz-coated sandstones, by the presence of oil in the pore
772 network.

773

774 **Conclusion**

- 775 1. Oil was present during quartz cementation in the Ula Formation in [Ula](#)
776 [Field](#) as revealed by the presence of oil inclusions suggesting oil ingress
777 into the reservoir began when the reservoir was at [a temperature of about](#)
778 [~100-120°C](#).
- 779 2. [Aqueous fluid inclusion homogenisation temperature data from primary](#)
780 [inclusions in quartz cement shows that](#) $T_{\text{quartz cementation}}$ seems to have
781 started at [an absolute minimum of 103°C with most quartz cement grow-](#)
782 [ing at >120°C](#), if [assume that](#) the [lower](#) homogenisation temperatures for

783 aqueous inclusions in quartz are regarded as being representative of mini-
784 mum growth temperature.

785 3. For sandstones of the same depositional facies, with ~~the same~~similar grain
786 size, similar ~~same~~ detrital clay content, similar ~~same~~ low quantity of grain
787 coating microquartz and similar ~~same~~ low quantity of ferroan dolomite,
788 there is less quartz cement in the oil leg than in the water leg, particularly
789 for facies 1 (~~coarse~~medium-grained graded sandstone) and facies 2 (fine-
790 to medium-grained bioturbated sandstone).

791 4. For facies 3 (fine- to very fine-grained bioturbated sandstone) there ap-
792 pears to be little quartz cement, regardless of whether oil was present dur-
793 ing diagenesis or not. This can be attributed to the (relatively) large quan-
794 tity of grain-coating microquartz and detrital clay associated with this fa-
795 cies.

796 5. A small number of the coarse-grained sandstone samples in the water leg
797 also have a few percent grain-coating microquartz. These have unusually
798 reduced quantities of quartz cement showing that microquartz, as well as
799 oil emplacement, can inhibit quartz cementation.

800 6. Emplacement of oil before, or during, quartz cementation has inhibited the
801 growth of quartz cement in the Ula Formation in the cleaner, fine- to me-
802 dium-grained and medium-grained graded, minimally microquartz ce-
803 mented sandstones.

804

805 **FIGURE CAPTIONS**

806 | Figure 1. Location map of the Central Graben showing [Ula Field](#) with insert map of
807 | the North Sea region (lower left). The map shows the study area in the black square
808 | and inserted field structural map right showing major bounding faults structures and
809 | well locations (modified from Nedkvitne et al., 1993).

810 | Figure 2. Generalized stratigraphy of [Ula Field](#) ~~modified from Fraser et al. (2002)~~.
811 | The Mandal Formation is the main regional source rock; the Ula Formation is the
812 | reservoir under consideration.

813 | Figure 3. Thermal ~~and burial history~~ curves ~~of for~~ [Ula Field](#) from well 7/12-6 (Fig.
814 | 1), ~~grey the heavier black line~~ represents the [top of the Ula](#) reservoir interval. [The](#)
815 | [combined Bburial and thermal](#) history ~~curve was~~ modelled using ~~Thermodel for~~
816 | [WindowsBasinMod](#) software.

817 | Figure 4. Comparison of core analysis porosity and wireline-derived porosity for
818 | well 7/12-A13.

819 | Figure 5. Plots of density-derived porosity and Archie-derived water saturation (S_w)
820 | from four of the five Ula field wells used in this study.

821 | Figure 6. Plots of core analysis porosity and permeability subdivided by wireline
822 | derived water saturations for the three facies; (a) [CoarseMedium](#)-grained graded
823 | sandstone facies, (b) [Fine- to medium-grained](#) bioturbated sandstone facies, (c) Very
824 | fine- to fine-grained bioturbated sandstone facies.

825 | Figure 7. Ternary diagram showing the Ula Formation sandstone classification
826 | (McBride, 1963).

827 Figure 8. Generalised paragenetic sequence for the Ula Sandstone in Ula Field (7/12-
828 2, 7/12-A3, 7/12-5, 7/12-A08 and 7/12-A13). Age ranges of diagenetic phases are
829 estimated based on thin sections and SEM observations.

830 Figure 9 a) SEM image showing framboidal pyrite (py) and microcrystalline quartz
831 (μ qz) formed early within intergranular area (7/12-A3, ~~3690.903520.36 m~~DDTVD,
832 Sw 0.61) b) SEM image showing partial dissolution of detrital K-feldspar grain (KF)
833 and later authigenic quartz within the secondary intragranular pore (sip) (Well 7/12-
834 5, 3894.00 mDD, Sw 0.78). (c) quartz overgrowth (qzo) encloses pore-filling chlorite
835 (ch) shown by circle (Well 7/12-5, 3894.00 mDD, Sw 0.78) suggesting quartz
836 precipitation after chlorite. (d) late hairy illite (i) draped quartz overgrowths (7/12-
837 A3, ~~3690.903520.36 m~~TVD~~DD~~, Sw 0.61). (e) Optical thin section photomicrograph
838 (plane polarised) showing feldspar overgrowths (kfo) and quartz overgrowths both of
839 which thin at grain contacts (circled) suggesting precipitation after main phase of
840 compaction (7/12-A3, ~~3675.503515.76 m~~DDTVD, Sw 0.~~6335~~). (f) residual
841 hydrocarbons (rh) which stain earlier quartz overgrowths (7/12-2, ~~3440.003407.93~~
842 ~~m~~DD TVD, Sw 0.~~0643~~).

843 Figure 10 (a) Thin section photomicrograph (plane polarised light) showing patchy
844 clay minerals (PC) and dolomite cement (dol) (7/12-2, ~~3419.93389.92 m~~DD TVD,
845 Sw 0.~~1305~~). (b) Thin section image (plane polarised) showing quartz overgrowths
846 which partially fills primary intergranular pore (PP) and stained by residual
847 hydrocarbons (rh) (7/12-2, ~~3460.003427.67 m~~DDm TVD, Sw 0.~~2413~~). (c) Thin
848 section photomicrograph (plane polarised light) showing clean primary porosity (PP)
849 ~~low-medium to high~~ volume of quartz overgrowths (qzo) and uncoated quartz grain
850 (Q) (7/12-~~A213~~, ~~3437.303706.32 m~~DD TVD, Sw 0.~~62.12~~). (d) Thin section

851 photomicrograph (plane polarised light) showing quartz overgrowths (qzo) occluding
852 primary pores around quartz grain 7/12-A3, ~~3686.60~~3525.35 m ~~TVD~~DD, SW
853 ~~0.60~~31). (e and f) Backscattered electron image and cathodoluminescence image of
854 the same sample differentiating between detrital quartz (Q) and quartz overgrowths
855 (qzo) in the later. Note that it much easier to observe quartz cement-grain boundaries
856 using light optical images than e-problem of quantifying the volume of quartz
857 overgrowths from the-backscattered electron images. (7/12-A3, 3525.35 m TVD, SW
858 0.31~~3686.60 mDD, Sw 0.60~~).

859 Figure: 11. SEM micrographs of minimally quartz cemented samples of medium-
860 grained graded facies 1 from the oil leg revealing the lack of microquartz or any
861 other sort of grain coating material. The exposed quartz grain surfaces contain
862 nascent quartz cement but are largely in their original, depositional, state. qzo:
863 quartz overgrowth, cs: clean grain surface free of microquartz but also with no quartz
864 cement growing. (a and inset b) 7/12-2, 3419.9~~3389.92~~ m ~~core depth~~TVD; Sw 0.05.
865 (c and inset d) 7/12-2 3414.95~~3384.98~~ m ~~TVD~~core depth; Sw 0.05.

866 Figure: 12. Variation of log-derived water saturation, core analysis porosity, quartz
867 cement, microquartz~~zz~~ and detrital clay with true vertical depth for all the wells
868 studied. Samples have been split into the three main facies. The diagram represents
869 the aggregation of data from four wells; -with the data are in depth order and do not
870 represent the stratigraphic succession necessarily repeated four times.

871 Figure 13. (a) Thin section image of microquartz-coated sandstone (7/12-2;
872 3395~~3365.4070~~; m ~~TVD~~DD; Sw 0.19). (b) SEM image showing grain-coating
873 microcrystalline quartz (μ qz) and mesoquartz (mqz) crystals (7/12-A3;
874 3690.90~~3534.87~~ m ~~TVD~~DD; Sw 0.75~~55~~).

875 | Figure 14. Point-counted quartz cement plotted against: (a) point-counted
876 | microquartz cement for all samples, and (b) for a subset of the samples, the
877 | percentage of grains coated with microquartz. Samples with abundant microquartz
878 | (and grain coating) have little quartz cement suggesting that microquartz has
879 | effectively inhibited quartz overgrowths. However, there are many samples with
880 | little microquartz (and grain coating) that also have little low quantities of quartz
881 | overgrowths suggesting that there is another factor that has significantly affected the
882 | growth of quartz cement.

883 | Figure 15. Thin section photomicrograph showing fluid inclusions; [see Table 2 for](#)
884 | [details of samples in the images](#). (a) Plane polar showing fluid inclusion assemblage
885 | in quartz cement. (b) Plane polar photomicrograph showing fluid inclusion rim at the
886 | boundary between detrital quartz grain and quartz cement samples from water zone
887 | well 7/12-A3. (c and d) petroleum inclusion under fluorescence light samples from
888 | oil leg of 7/12-2.

889 | Figure 16. Homogenization temperature measurements for aqueous and petroleum
890 | inclusions in selected samples of the Ula Formation. Note present-day reservoir
891 | temperature is only available for well 7/12-A3

892 | Figure 17. Diagram, based on petrographic data, illustrating styles of porosity-loss in
893 | the Ula Formation ([after](#) Houseknecht, 1984). The oil leg samples ($S_w < 0.5$) have
894 | relatively more porosity lost to compaction than cementation. In contrast, the water
895 | leg samples ($S_w > 0.5$) have more porosity lost to cementation than compaction ~~and~~
896 | ~~64% lost to~~. This diagram suggests that, on average, the water leg is more cemented
897 | than the [oil leg](#).

898 Figure 18. Point-counted quartz cement volume versus wireline-derived water
899 saturation; (a) ~~coarse~~medium-grained graded sandstone facies 1 (b) fine- to medium-
900 grained bioturbated sandstone facies 2 (c) very fine- to fine--bioturbated facies 3.
901 This diagram shows that the fine- to medium-grained bioturbated and medium-
902 grained graded facies have less quartz cement in samples with low water saturation
903 than those with higher water saturation. This suggests that oil emplacement has
904 inhibited the growth of quartz cement. Note that microquartz coatings also play a
905 role in diminishing the amount of amount of quartz cement.

906 Figure 19. Wireline-derived water saturation values for medium-grained graded
907 sandstone facies 1 samples, that have less than 20% grain coating, compared to
908 quartz cement and core analysis data. (a) Water saturation compared to quartz
909 cement showing that these sandstones have decreasing quartz cement in samples with
910 decreasing water saturations. Sandstones with water saturations less than 0.5 have
911 less than 5% quartz cement; those with water saturations greater than 0.5 have up to
912 15% quartz cement. There is a good correlation between water saturation and quartz
913 cement; this relationship could be used to predict quartz cement as a function of
914 water saturation. (b) Water saturation compared to core analysis porosity showing
915 that these sandstones have increasing porosity with decreasing water saturation. (c)
916 Water saturation compared to core analysis permeability showing that these
917 sandstones have increasing permeability with decreasing water saturation. (d) Quartz
918 cement compared to core analysis porosity showing that less quartz cement equates
919 to higher porosity.

920

921 **TABLE CAPTIONS**

922

923 Table 1. Average values of core analysis horizontal permeability porosity, and point
924 count quartz cement, detrital clay, microquartz and ferroan dolomite volumes for the
925 different facies, subdivided by high and low water saturation. [A full listing of all](#)
926 [petrographic and related data is available in Appendix 1.](#)

927

928 Table 2. The properties of fluid inclusion samples in different wells of [Ula Field](#).

929

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