

Hydrocarbon filling and leakage history of a deep geopressured sandstone, Fulmar Formation, United Kingdom North Sea

Mark Wilkinson, R. Stuart Haszeldine, and Anthony E. Fallick

ABSTRACT

Diagenetic minerals in a water-filled borehole from the Jurassic Fulmar Formation, United Kingdom central North Sea, record two phases of hydrocarbon filling and emptying. Initial oil charge was during the Late Cretaceous, at shallow burial depths of about 1.5 km (0.9 mi). As we consider that hydrocarbon has preserved porosity during burial, this has implications for the understanding of the porosity evolution of the Fulmar Formation, which, in other locations, is an important hydrocarbon reservoir. The early oil charge, as recorded by illite K-Ar ages, progressively filled the structure from 84 to 59 Ma, and possibly precipitated bitumen because of biodegradation. The first oil predated many of the burial diagenetic reactions within the sandstone. After leak-off at ca. 60 Ma, diagenetic reactions continued in an open geochemical system, with possible import of CO₂. Products of these reactions include ankerite and quartz overgrowth cements. Hydrocarbon staining postdates these phases and provides evidence of a hydrocarbon charge, probably gas condensate. The second hydrocarbon charge also leaked off, and the sandstone is now water bearing. Previous work on the Fulmar Formation has incorrectly placed all the diagenetic reactions as pre-dating the first arrival of hydrocarbon. The present-day pore fluids are high-salinity, high- $\delta^{18}\text{O}$ fluids derived from the underlying Permian Zechstein evaporates. These fluids entered the reservoir during a phase of overpressure release that caused fracturing of the framework quartz grains, possibly coincident with the second phase of hydrocarbon leak-off at 2–5 Ma.

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INTRODUCTION

An assessment of petroleum migration and filling history is essential for a full understanding of a petroleum basin and is required for the ranking of undrilled prospects. Here, we demonstrate that it is possible for a reservoir to fill and empty more than once during burial. This is a concept that petroleum geologists have begun to consider only recently. In the case of the study well from the United Kingdom central North Sea, each period of filling or emptying has been recorded by petrographic, isotopic, or fluid-inclusion evidence derived from oil exploration core. The relationship between hydrocarbon emplacement and diagenesis has also been controversial, with many authors assuming that the emplacement of hydrocarbons terminated all significant diagenesis. Here, we present evidence for diagenesis continuing after oil emplacement, albeit after the leak-off of the initial oil charge. An understanding of diagenesis is required if prediction of reservoir quality is to be made away from boreholes, especially, for example, into the aquifer.

Previous evidence for multiple episodes of charging in hydrocarbon reservoirs has been established from the description of paleo-oil-water contacts. Such contacts have been identified from studies of petroleum geochemistry (Leythaeuser et al., 2000) or by changes of bulk cementation leading to changes of reservoir quality (Heasley et al., 2000; Marchand et al., 2000). Detailed analysis of petroleum systems has shown that some reservoirs have had multiple fills of hydrocarbons of contrasting types, e.g., oil followed by gas (Bhullar et al., 1999; Swarbrick et al., 2000; Isaksen et al., 2002); and dry wells, presently containing water but with pervasive indications of the previous presence of hydrocarbon, prove that filled reservoirs can lose their hydrocarbon charge. This can happen because of seal failure, for example. Comparison and calibration of basin models of hydrocarbon generation and migration are now possible. Here, we present diagenetic evidence from the Fulmar Formation of the United Kingdom central North Sea to support the hypothesis that some reservoirs have had complex charging histories, with multiple phases of filling and emptying.

The emplacement of oil into a sandstone before the onset of the major diagenetic reactions can prevent chemical compaction and the associated cementation (Heasley et al., 2000; Bloch et al., 2002; Marchand et al., 2002; Wilkinson et al., 2004). Hence, early oil charge can preserve reservoir quality, potentially to great depths of burial. Because the Fulmar Formation has exceptional porosity (up to 30% porosity at greater than 5 km [3.1 mi] burial depth; Lasocki et al., 1999), the mechanisms of porosity preservation or enhancement are clearly of economic interest.

APPROACH

We observe that the Central Graben is today an active and dynamic fluid system, with highly overpressured sands leaking fluid into overlying, less overpressured units (see Moss et al., 2003). As

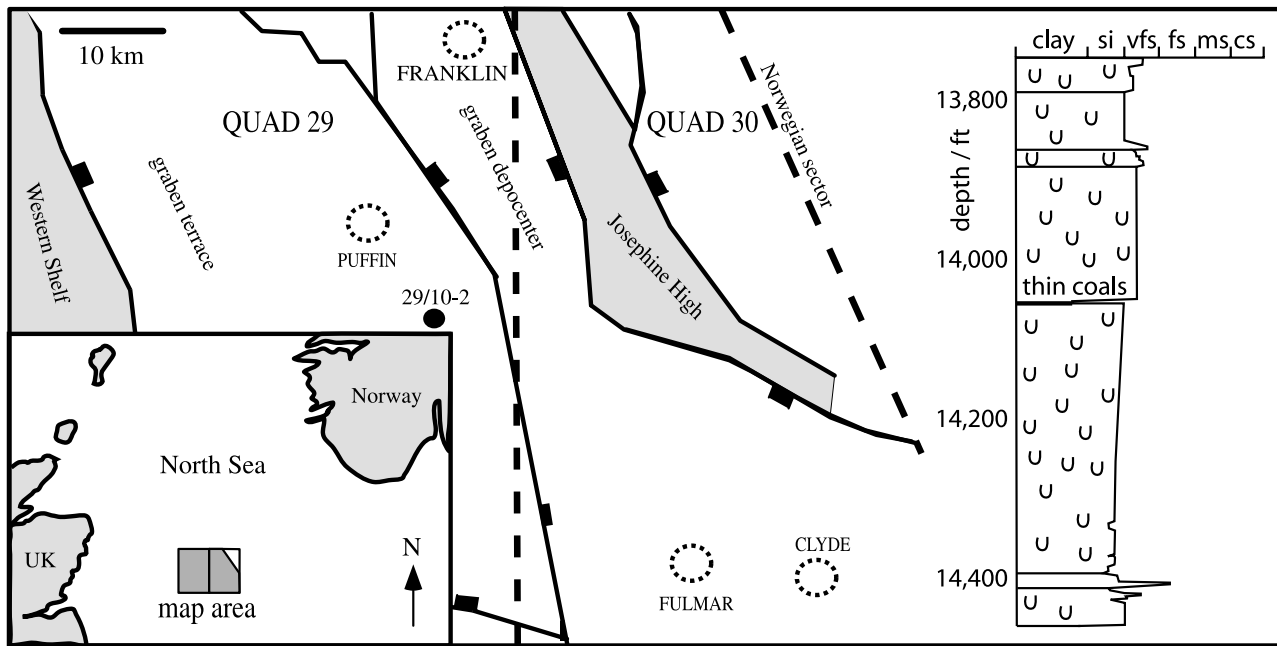


Figure 1. Location map showing well 29/10-2 and the oil fields (dashed ovals) named in the text. The summary sedimentary log is based on detailed figures of Carruthers et al. (1996) and Howell et al. (1996), showing the entire cored section of the Fulmar Formation in well 29/10-2. Note that the grain size is almost entirely within the very fine sand (vfs) category. Sedimentary structures are mostly restricted to occasional horizontal bedding because the sands are highly bioturbated.

part of this progress, oil can both fill and be lost from traps, as proven by present-day dry holes with dead oil or bitumen showing the previous presence of substantial oil columns (Lomando, 1992). We hypothesize that the filling and emptying of traps may have occurred in the geological past. This article draws together several lines of evidence to show that this is indeed the case:

1. K-Ar ages of fibrous authigenic illite date oil charging at 84–59 Ma.
2. Basin modeling permits the generation of hydrocarbons from source areas from 85 Ma, with migration into adjacent, shallow structures that were at only 55°C and 1.6 km burial depth.
3. Most of the authigenic phases postdate the early illite.
4. Bitumen (dead oil) stains late authigenic carbonate and covers quartz overgrowths.
5. Fluid inclusions in healed quartz grains provide evidence for pressure release and the ingress of highly saline water late in the burial history.

GEOLOGICAL SETTING

The United Kingdom central North Sea is an important petroleum province, and the principal reservoir is the Fulmar Formation, an Upper Jurassic, shallow-

marine sandstone (Howell et al., 1996). In the central North Sea, sediments of Paleozoic to Holocene age lie in an approximately northwest-southeast-oriented extensional graben, where structures are dominated by normal faulting and salt movement. Isaksen (2004) includes a brief discussion of the structural evolution of the area, source references, and cross sections. The function of salt in controlling the structural evolution of the area is described by Howell et al. (1996). The most important source rock is the Late Jurassic Kimmeridge Clay, the thermal evolution of which is described in detail by Isaksen (2004). Many of the fields currently have a charge of gas condensate, although this is thought to be a replacement of an original oil charge (Isaksen, 2004).

The study well, 29/10-2, was drilled by Shell on a structural high that bounds the western side of the western arm of the south Central Graben in the United Kingdom central North Sea (Figure 1). The well was found to be dry, i.e., not to contain hydrocarbons in economic quantities, and was abandoned. A thick sequence of Fulmar Formation, in excess of 200 m (660 ft), is present. The sands are predominantly aggradational and of fine to very fine grain size. Few primary sedimentary structures are preserved because of pervasive bioturbation. A rooted coal, which is rare within the Fulmar Formation, implies subaerial exposure and the presence of a shoreline. However, the Fulmar Formation is

generally interpreted as a shallow-marine sandstone, extensively reworked by tides and currents within a moderately confined shelf sea (Howell et al., 1996). Detailed sedimentary logs of well 29/10-2 are presented by Carruthers et al. (1996) and Howell et al. (1996). The sedimentary log is summarized in Figure 1.

The basic petrography of the Fulmar Formation sands in well 29/10-2 has been described by Wilkinson et al. (1994) and figured in Wilkinson and Haszeldine (1996). Previous work on the Fulmar has emphasized the importance of diagenesis in the preservation of reservoir quality during burial—at least 50% of visible porosity is identified as being secondary in origin, mostly formed by the dissolution of K-feldspars (Lasocki et al., 1999). The preservation of this secondary porosity has been attributed to high overpressures in reservoir intervals, and it has been suggested that in some cases, the porosity of the sands has actually increased during late stages of burial (Wilkinson et al., 1997).

The diagenetic history of the Fulmar Formation sands, as published, has been described as being relatively simple (Stewart, 1986; Clelland et al., 1993; Wilkinson et al., 1994; Lasocki et al., 1999), with hydrocarbon emplacement as the last important diagenetic event to have occurred. None of the published paragenetic sequences imply any interaction between diagenesis and hydrocarbon emplacement, except perhaps that, as the last event, hydrocarbon emplacement may have terminated any ongoing diagenetic reactions. However, our detailed study reveals a more complex interaction between hydrocarbon emplacement and diagenesis than has been previously described and a more complex history of petroleum charging than has been previously suspected.

No published model exists for the isotopic evolution of the pore fluids within the Fulmar Formation, although two studies have used isotopic data from well 29/10-2 in an attempt to constrain the pore-fluid evolution. Wilkinson et al. (1994) attempted to use stable isotope ratios of illite to constrain the origin of the early pore fluids within the well, while Darby et al. (1997) interpreted K-Ar age dates in terms of pore-fluid flow events. The K-Ar ages of Darby et al. (1997) have a range from 84 to 59 Ma, corresponding to a temperature of only about 50°C because of the shallow burial depth of the Fulmar Formation in well 29/10-2 at that time. Consequently, Darby et al. (1997) dismissed the possibility that the illite recorded hydrocarbon filling (although K-Ar ages of illite are commonly linked to hydrocarbon filling; Hamilton et al., 1992; Wilkinson and Haszeldine, 2002). Instead, Darby et al. (1997) interpreted the K-Ar ages as being caused by pore-water

flushing because of the onset of basinwide subsidence. The stirring of the pore fluids within the Fulmar Formation was hypothesized to increase the rate of illite precipitation significantly, such that the large volume of illite precipitated at this time recorded the age of the dewatering event. In this article, we reinterpret the K-Ar ages of Darby et al. (1997) as being caused by a Late Cretaceous hydrocarbon charge at shallow depth.

The burial history of the Fulmar Formation in well 29/10-2 is relatively simple (figure 4 of Darby et al., 1997; see below). The west Central Graben area underwent only minor subsidence prior to the Late Cretaceous, when the rate of subsidence increased substantially. Well 29/10-2 differs slightly from this regional pattern because of the influence of local salt tectonics (Darby et al., 1997). At between 2 and 5 Ma, the rate of subsidence increased again, resulting in about 1 km (0.6 mi) of burial since this time (Darby et al., 1997; Isaksen, 2004). The Fulmar Formation in this well is currently at its maximum depth of burial, and it is reasonable to presume that the rocks have never exceeded the present-day temperature.

METHODS

Well 29/10-2 was studied as part of a regional investigation of the Fulmar Formation. Forty blue-dyed, resin-impregnated thin sections from this well were cut and point counted with 200 counts per slide. Most of the thin sections were polished for examination on a scanning electron microscope (SEM). The petrographic sequence was constructed from observations on both thin sections and chips of rock on the SEM.

Authigenic ankerite and dolomite are intergrown and impossible to separate physically for analysis. Stable isotope ratios ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) were hence conducted on mineral separates that contained a mixture of both ankerite and dolomite, as described by Hendry et al. (2000a, b). The percentage of each mineral in the separates was determined by image analysis of backscatter scanning electron micrographs (BS-SEM), and the end-member compositions were calculated (Figure 2). Whole rock analyses were also performed using a sequential technique. This is acceptable because the samples contain only ankerite and dolomite and lack other carbonate phases. The samples were reacted with phosphoric acid at 25°C for 3 hr, and the CO_2 was extracted and analyzed. The remaining sample was then heated to 100°C and left overnight, which dissolved all remaining carbonate. The CO_2 from this

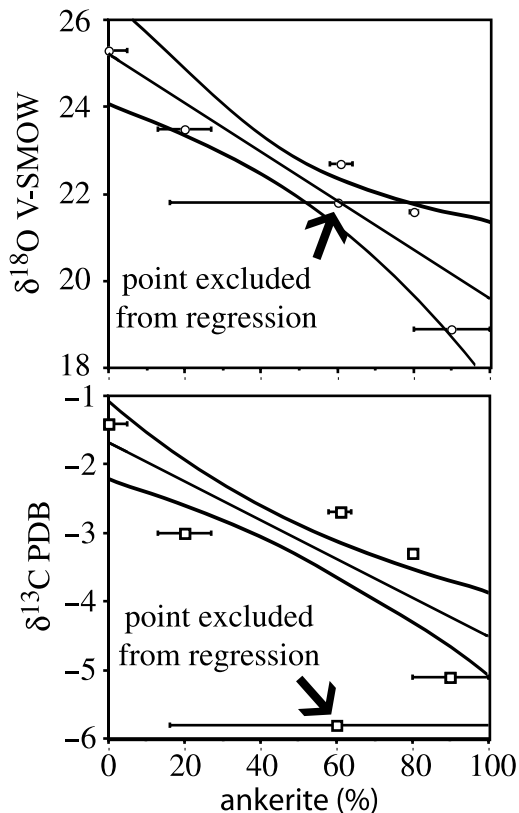


Figure 2. Plots to determine the isotopic composition of the end-member dolomite and ankerite. These phases cannot be separated for analysis, and the intergrowths are too fine grained for in-situ laser analysis. The percentage of ankerite and dolomite was determined by point-counting BS-SEM images of the separates used for analysis, with error bars at 2 standard errors. The curves shown are one standard error about the regression line. Note that one of the points was excluded from the regression because the uncertainty in the sample composition was deemed to be too high.

reaction was also extracted and analyzed. The quartz overgrowth compositions were determined by conventional separation and analytical techniques (Brint, 1989). All isotopic results are presented in standard notation relative to the Vienna standard mean ocean water (V-SMOW) standard, except for $\delta^{13}\text{C}$, which is relative to the Peedee belemnite (PDB) standard.

Mineral-water fractionation factors are from Friedman and O'Neil (1977, quartz), Land (1983; dolomite, Fisher and Land (1986; ankerite), and Savin and Lee (1988; illite). Jurassic meteoric water is taken to have $\delta^{18}\text{O} = -5$ to -7% V-SMOW (Marshall and Ashton, 1980; Hudson and Andrews, 1987). Present-day pore-water samples from the study well are not available. However, pore-water samples from the Fulmar Formation of the nearby Franklin field (Figure 1) were analyzed for

stable oxygen and hydrogen isotope ratios using methods and standards described in Wilkinson et al. (2004).

Fluid inclusions were studied using double-polished wafers 40–100 μm thick, prepared so as to avoid unnecessary stress and temperatures exceeding 50°C . Temperature of homogenization (T_h) was determined using a Reynolds gas flow U.S. Geological Survey–modified stage mounted on a Leitz Ortholux II microscope. Ultraviolet fluorescence was conducted on the same microscope. The salinity of the fluid within the inclusions, as equivalent NaCl, was estimated using the freezing temperature of the fluid (Roedder, 1984).

RESULTS

A summary of the average composition of the Fulmar Formation in well 29/10-2, derived by optical point counting of thin sections, is given in Table 1. All the thin sections show extensive staining by hydrocarbon over the entire range for which core is available (13,745–14,452-ft [4190–4405-m] driller's depth). Bitumen is predominantly located within primary pores, where it is commonly seen to be pore lining. The bitumen is very rarely sufficiently abundant to fill pores. Although the bitumen is commonly attached to the mineral surfaces, which define the pore, it is sometimes not attached to the bounding mineral surfaces. This is interpreted as being caused by the bitumen having shrunken, possibly during sample cleaning or impregnation with resin. The

Table 1. Average Composition of the Fulmar Formation in Well 29/10-2

	Average Content	2SE*
Quartz	56	6
K-feldspar	9	2
Plagioclase**	3.9	0.9
Lithic fragments	2.5	0.3
Oil-stained clay [†] and bitumen	11	6
Ankerite	1.3	0.6
Dolomite	2.5	0.7
Quartz overgrowth	2.2	0.9
Primary porosity	7	2
Secondary porosity	1.7	0.4

*SE = Standard error.

**Includes authigenic albite as a replacement phase.

[†]Mostly illite. Discrimination of detrital and authigenic clay is impossible in thin section.

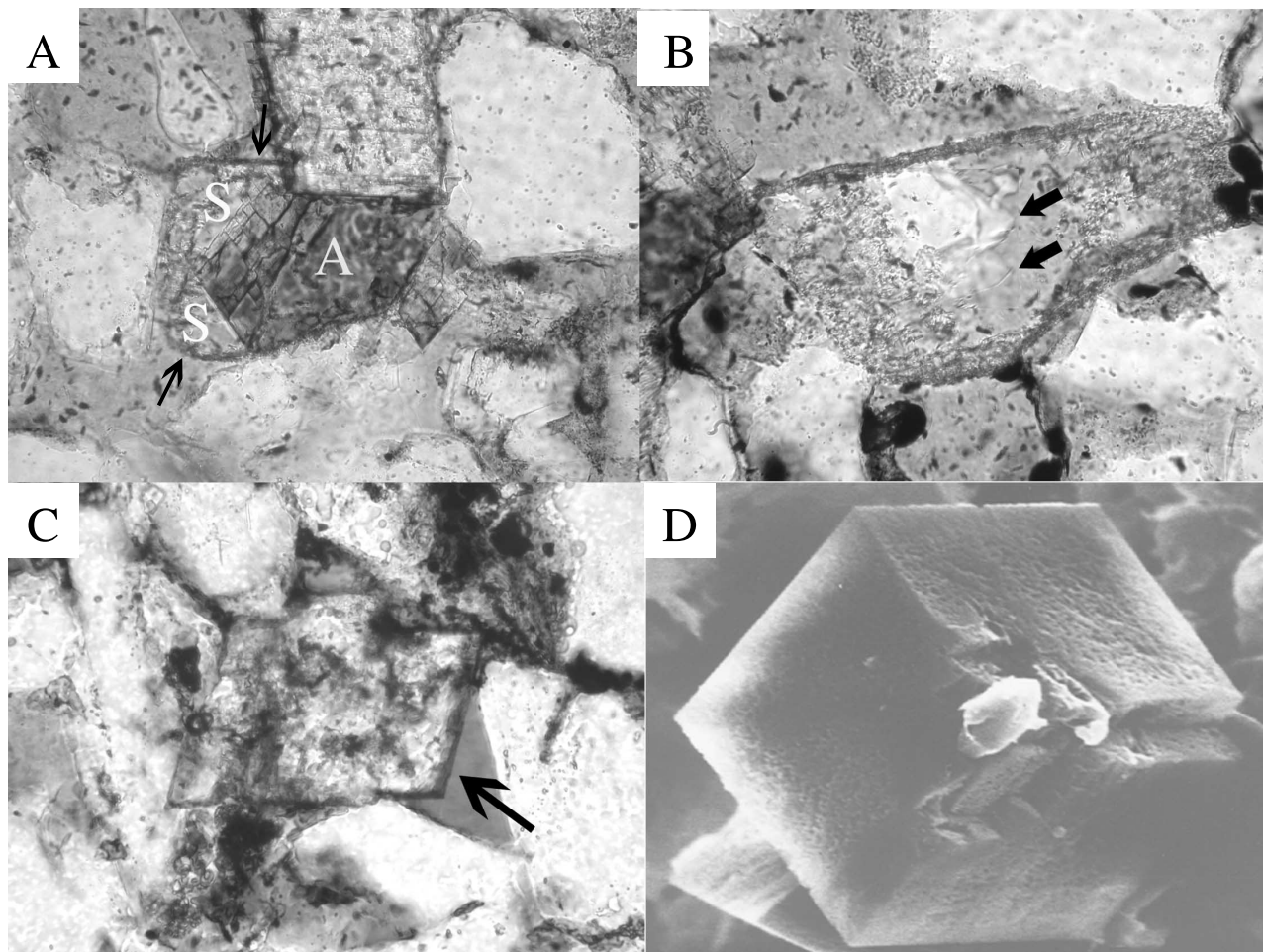


Figure 3. (A) A secondary pore (S) partly infilled by ankerite (A). The pore was formed by the diagenetic dissolution of a detrital K-feldspar grain, defined by a rim of oil- and bitumen-stained clay (arrows). Note the lack of bitumen and hydrocarbon inside the pore. This texture indicates that the bitumen formation predates K-feldspar dissolution. The ankerite is observed either to grow into the secondary pores, as in this case, or to stop at the margins of the pores. This is interpreted to indicate that the feldspar dissolution and the growth of the ankerite were contemporaneous. Field of view (FOV) = 120 μm . (B) A secondary pore after feldspar dissolution with a quartz overgrowth (black arrows). The quartz overgrowths are observed either to grow into the secondary pores, as in this case, or to stop at the margins of the pores, indicating that the feldspar dissolution and the growth of the quartz overgrowths were contemporaneous. FOV = 120 μm . (C) Authigenic ankerite with a bitumen-stained rim, highlighted by a black arrow. Note that the euhedral outline of the dolomite crystal shows that the black color is not a superficial coating of bitumen on a crystal surface. The bitumen is retained within microporosity at the margins of the grain, see (D). Thin-section photomicrograph. FOV = 180 μm . (D) Scanning electron microscopy photomicrograph of authigenic ankerite crystal with superficial etching. The microporosity is infilled with bitumen, producing the stain in (C). FOV = 30 μm .

bitumen is not generally present within secondary pores, which were primarily formed by the dissolution of feldspars. Bitumen is, however, observed within the microporosity in expanded mica flakes and within dissolutional microporosity in perthites. The quantity of bitumen present is difficult to assess because it is frequently intergrown with grain-rimming clays, which are, in any case, stained by hydrocarbon to a dark-brown color in thin section. Table 1 therefore has a combined figure for the abundance of clays and bitumen ($11 \pm 6\%$).

In many cases, secondary pores formed by the dissolution of K-feldspar have well-preserved rims, interpreted to have formed from either early authigenic feldspar overgrowths and/or clay coatings (Figure 3A, B). The secondary porosity rims appear to be dark in thin section because of impregnation with bitumen. The clay coatings are much more abundant on feldspar grains than on detrital quartz grains. Bitumen coats both ankerite and quartz overgrowths, and hence, at least some of the bitumen postdates these phases.

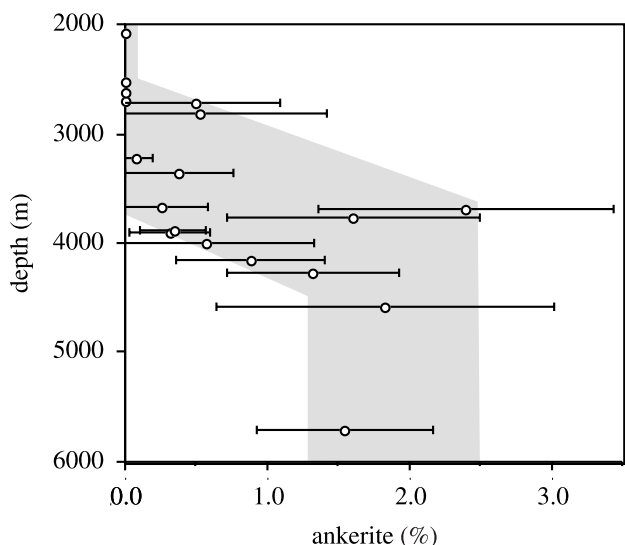


Figure 4. Regional abundance of ankerite versus depth for the Fulmar Formation. Each point is a single well, with 2SE bars. Ankerite is absent from above 2700 m (8858 ft) and increases in abundance down to about 4500 m (14,700 ft) burial depth. The shaded area shows the interpretation of the data trend.

K-feldspars in well 29/10-2 are observed in all stages of preservation, from pristine to relics defined only by remnant overgrowths and clay coatings (Figure 3A, B). Clearly, K-feldspar dissolution is an important diagenetic process, generating secondary porosity that, in other Fulmar Formation fields, can be 50% of all preserved porosity (Lasocki et al., 1999). Identifiable secondary porosity is much less abundant in well 29/10-2 than in other Fulmar Formation wells (e.g., Lasocki et al., 1999). The secondary pores are not commonly filled with the clay minerals (illite or kaolin), which might be expected to precipitate as a by-product of feldspar dissolution. However, clay pseudomorphs after feldspar are also common (Stewart, 1986; Wilkinson et al., 1994). These are similar to strongly sericitized feldspars in appearance, but are thought to be the result of diagenetic alteration of K-feldspars during burial.

Almost all the thin sections contain a dispersed dolomite-ankerite cement, with cores of dolomite overgrown by rims of syntaxial ankerite (Figures 3A, 4). The cement crystals are similar to that of the nearby Franklin and Elgin fields, which have been extensively described and illustrated by Hendry et al. (2000a, b). However, in contrast to the Franklin and Elgin examples, the grains from well 29/10-2 have an apparent stain of a dark-brown color that penetrates some 10–100 μm into the grain surface and is visible in thin section (Figure 3C). The stain is only developed on ankerite surfaces that have

grown into primary porosity and not those surfaces that touch detrital grains or secondary pores. The stain sometimes penetrates cracks within the ankerite into the centers of the crystals. The stain also sometimes penetrates the boundaries between adjacent ankerite crystals, where two crystals have grown in contact. Where the outer surface of the ankerite is covered by bitumen, then the stain is not developed. Scanning electron microscopy examination of chip samples reveals that the surfaces of the dolomite-ankerite grains are pitted (Figure 3D). We infer that these pits are filled with bitumen, so producing the stain. The stain is not luminescent in ultraviolet (UV) light, and so cannot be undegraded oil. Note that, regionally, ankerite is absent from sands buried to less than 2700 m (8858 ft) and increases in abundance over the interval 2700–4500 m (8858–14,763 ft) (Figure 4).

Stable oxygen and carbon isotope ratios of the dolomite and ankerite show a clear positive correlation (Figure 5; Table 2). Whole rock and separated samples have similar ranges. Compositions of the end-member ankerite and dolomite phases have been calculated for two rock samples using ankerite-dolomite ratios measured by BS-SEM, and these are also plotted (Figures 2, 5). The correlations between ankerite-dolomite ratio and isotopic composition are good, leading to reasonable estimates of the dolomite composition ($\delta^{18}\text{O} = 24\text{--}27\text{‰}$ V-SMOW; $\delta^{13}\text{C} = -1$ to -1.7‰ PDB). The estimate

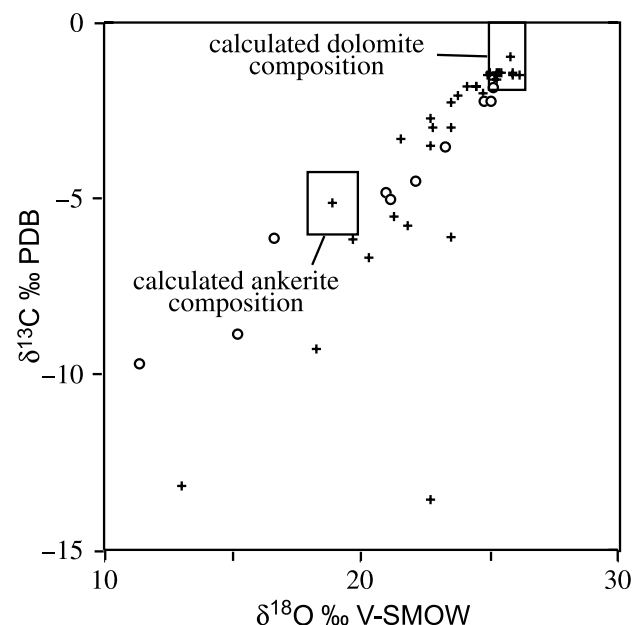


Figure 5. Stable isotopic data for mixed ankerite and dolomite samples. Circles are whole rock samples, crosses are separates with enriched concentrations of either ankerite or dolomite, see text. Estimated compositions of pure ankerite and dolomite are shown.

Table 2. Stable Oxygen and Carbon Isotope Ratios for Authigenic Carbonates*

Depth (m)	Grain Size (μm)	Extraction Method**	Magnetic Number [†]	$\delta^{13}\text{C}$ ‰ PDB	$\delta^{18}\text{O}$ ‰ V-SMOW	% Ankerite \pm 2SE
4221.2	75–63	D	1	–1.8	25.2	
4221.2	75–63	D	2	–2.1	23.8	
4221.2	75–63	D	3	–9.3	18.3	
4221.3	150–125	D	1	–1.6	25.2	
4221.3	150–125	D	2	–2.0	24.8	
4221.3	150–125	D	3	–3.5	22.7	
4221.3	106–90	D	1	–1.5	26.2	
4221.3	106–90	D	2	–1.4	25.3	0 \pm 5
4221.3	106–90	D	3	–1.8	24.5	
4221.3	106–90	D	4	–3.0	23.5	20 \pm 7
4221.3	106–90	D	5	–5.8	21.8	60 \pm 44
4221.3	125–106	D	1	–1.4	25.9	
4221.3	125–106	D	2	–1.4	25.5	
4221.3	125–106	D	3	–1.8	24.5	
4221.3	125–106	D	4	–5.5	21.3	
4221.3	90–75	D	1	–6.7	20.3	
4221.3	90–75	D	2	–1.6	25.3	
4221.3	90–75	D	3	–3.0	22.8	
4221.3	90–75	D	4	–2.3	23.5	
4221.3	90–75	D	5	–1.4	25.0	
4221.3	90–75	D	6	–1.4	25.4	
4221.3	125–106	D	1	–1.5	25.9	
4221.3	125–106	D	2	–1.0	25.8	
4221.3	125–106	D	3	–1.5	25.3	
4221.3	125–106	D	4	–1.5	24.9	
4221.3	125–106	D	5	–1.8	24.1	
4267.3	75–63	D	1	–13.6	22.7	
4267.3	75–63	D	2	–6.2	19.7	
4267.3	75–63	D	3	–13.2	13.0	
4297.6	90–75	D	1	–6.1	23.5	
4355.8	75–63	D	1	–2.7	22.7	61 \pm 3
4355.8	75–63	D	2	–3.3	21.6	80 \pm 1
4355.8	75–63	D	3	–5.1	18.9	90 \pm 10
4199.2	Whole rock	A		–2.2	25.0	
4236.3	Whole rock	A		–1.8	25.1	
4297.6	Whole rock	A		–2.2	24.8	
4329.2	Whole rock	A		–4.8	20.9	
4356.0	Whole rock	A		–3.5	23.2	
4199.2	Whole rock	D		–9.7	11.3	
4236.3	Whole rock	D		–4.5	22.1	
4297.6	Whole rock	D		–5.0	21.1	
4329.2	Whole rock	D		–6.1	16.6	
4356.0	Whole rock	D		–8.8	15.2	

*Mixed ankerite and dolomite.

**D = extracted as for dolomite, i.e., overnight at 25°C; A = extracted for ankerite, i.e., the remnant from dolomite extraction reacted at 100°C overnight.

[†]Samples subdivided by magnetic separation. The magnetic numbers are only relative and cannot be compared between samples. Subsample 1 contains the most dolomite, and the others contain progressively less.

Table 3. Quartz Overgrowth Oxygen Isotope Ratios

Depth (m)	$\delta^{18}\text{O}$ (V-SMOW) Grain Core	Overgrowth in Grain Core (%)	$\delta^{18}\text{O}$ (V-SMOW) Bulk Grain	Overgrowth in Bulk Grain (%)	$\delta^{18}\text{O}$ (V-SMOW) Overgrowth
4221.3	10.96	10.2	12.50	28.3	18.5
4267.2	10.22	0	12.18	19.6	20.5
4355.8	10.76, 11.39	0	12.81, 12.77	25.2	18.5

of the isotopic composition of the ankerite end member is less well constrained ($\delta^{18}\text{O} = 18\text{--}20\text{‰ V-SMOW}$; $\delta^{13}\text{C} = -4$ to -6‰ PDB). Oxygen isotopic compositions of quartz overgrowths are listed in Table 3, and oxygen isotopic compositions of illite are reported in Wilkinson et al. (1994).

Fluid inclusions are rare within authigenic quartz in the samples chosen and are in the size range 1–6 μm . Most of the inclusions were located in healed fractures within quartz grains; only two measurable inclusions were located within quartz overgrowths. All the fluid inclusions suitable for analysis were filled with aqueous fluids. Homogenization temperatures ranged from 133 to 145°C (Table 4; Figure 6), with a modal value of 135–137°C. Estimated salinities for the trapped fluids range from 30 to 140 wt. % NaCl equivalent (Table 4; Figure 6). The stable isotopic composition of the present-day pore waters within the Fulmar Formation are in Table 5. Regionally, quartz overgrowths become more abundant over the depth interval 3000–5000 m (10,000–16,400 ft) (Figure 7).

K-Ar ages of authigenic illite from well 29/10-2 have been reported by Darby et al. (1997). Here, we note that the ages show an important and systematic pattern of decreasing age with increasing depth (Figure 8) that was previously not reported. Other petrographic data for the Fulmar Formation were reported by Wilkinson et al. (1994).

DISCUSSION

Illite K-Ar Ages Date Oil Charge

Authigenic illite in well 29/10-2 shows a pattern of decreasing age with increasing depth (Figure 8). The simplest interpretation for this must be that the illite grew synchronously with hydrocarbon charging into the reservoir (Hamilton et al., 1992). Hydrocarbon charging would have occurred between 84 and 59 Ma, implying reservoir temperatures of only 48–55°C (from the basin model of Darby et al., 1997). Oil generation began

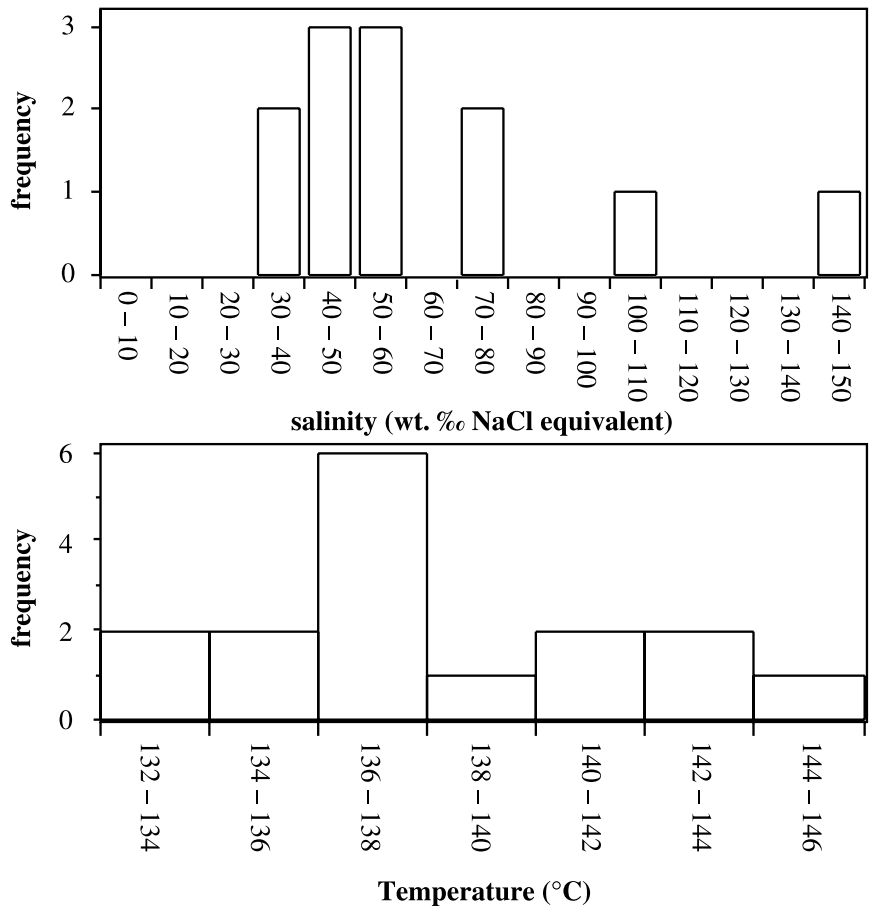
in the Central Graben in the Late Cretaceous (Lasocki et al., 1999), although the major phase of oil migration was later (early Miocene; Cornford, 1994). Well 29/10-2 lies on the footwall of a basin-scale normal fault, and the Kimmeridge Clay Formation (the likely source rock) is buried to considerable depths in the hanging wall. It is, hence, reasonable to assume that this very deeply buried source rock could have generated oil during the Late Cretaceous, which migrated vertically, probably along the line of the fault, into the 29/10-2 structure. Reservoir filling in this structure lasted for at least 25 m.y., possibly because of the slow rate of oil generation because only small volumes of the source areas would have been mature at this time. The mudrock seal to the Fulmar Formation reservoir would have been quite capable of retaining a substantial hydrocarbon column even at this relatively shallow depth, contrary to popular belief (figure 4.33 of Gluyas and Swarbrick, 2004). The oil

Table 4. Fluid-Inclusion Measurements

Depth (m)	T_h (°C)	Salinity (‰)	Inclusion Type
4267.1	135	100	Aqueous in quartz fracture
4267.1	143	*	Aqueous in quartz overgrowth
4267.1	138	75	Aqueous in quartz overgrowth
4267.1	135	38	Aqueous in quartz fracture
4267.1	138	40	Aqueous in quartz fracture
4267.1	137	40	Aqueous in quartz fracture
4267.1	143	30	Aqueous in quartz fracture
4267.1	138	50	Aqueous in quartz fracture
4267.1	145	40	Aqueous in quartz fracture
4267.1	133	50	Aqueous in quartz fracture
4267.1	137	50	Aqueous in quartz fracture
4267.1	138	140	Aqueous in quartz fracture
4267.1	141	*	Aqueous in quartz fracture
4267.1	140	*	Aqueous in quartz fracture
4267.1	142	*	Aqueous in quartz fracture
4267.1	132	*	Aqueous in quartz fracture

*Positive freezing temperature, so no value of salinity can be calculated.

Figure 6. Homogenization temperature and salinity data for aqueous fluid inclusions in healed fractures in quartz grains. Fluid inclusions in quartz overgrowths are mostly either absent or too small to measure.



may have been biodegraded to produce at least some of the bitumen present within the reservoir during filling, as discussed below. Note that there is no petrographic evidence for this early bitumen; for example, neither ankerite nor quartz overgrowths are seen to overlie bitumen. This may be because, where present, the early bitumen inhibited the formation of later cements.

Hydrocarbon Release 1

Given that there was oil in the 29/10-2 reservoir during the Late Cretaceous, how long did it remain there before leaking off? It is possible to loosely constrain this

Table 5. Stable Isotope Analysis of Produced Water from the Fulmar Formation of the Franklin Field

$\delta^{18}\text{O}$ V-SMOW	δD ‰ V-SMOW
4.3	-33
4.6	

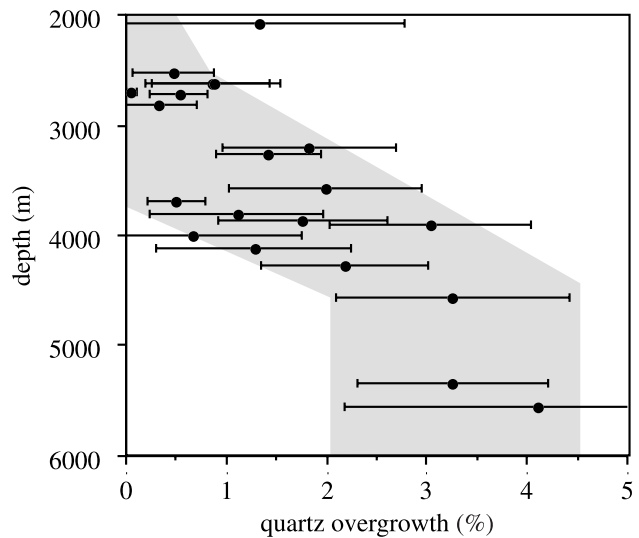


Figure 7. Regional abundance of quartz overgrowth cement versus depth for the Fulmar Formation. Each point is a single well, with 2SE bars. Overgrowths are uncommon above 2500 m (8200 ft) and increase in abundance down to about 4500 m (14,700 ft) burial depth. The shaded area shows the interpretation of the data trend.

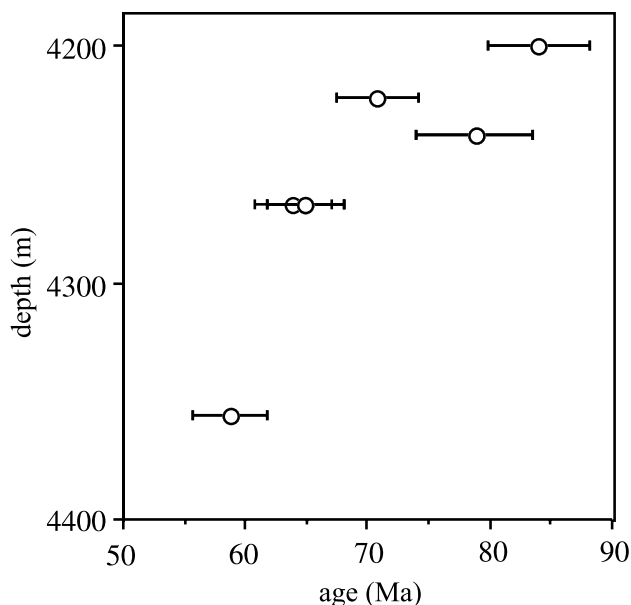


Figure 8. K-Ar age of authigenic illite versus depth for well 29/10-2. A clear decrease in age with depth is evident, which is most easily explained as caused by illite growth during oil filling of the sandstone. This supports the basin model of hydrocarbon filling during shallow burial before many of the later diagenetic reactions occurred.

using the evidence of late diagenetic reactions. It has been widely, although controversially, assumed that the presence of hydrocarbon in a sandstone will stop, or at least significantly retard, diagenetic reactions (Heasley et al., 2000; Marchand et al., 2000, 2001). This has been demonstrated for the Fulmar Formation, in the Fulmar field, by Saigal et al. (1992). It hence seems likely that, when the deep diagenetic reactions occurred (K-feldspar dissolution, quartz overgrowth, and ankerite precipitation), the pore fluids in the Fulmar Formation sandstone were predominantly aqueous.

Regional data show that there is no ankerite recorded in the Fulmar Formation buried to less than 2.7 km (1.6 mi) depth, and ankerite increases from about 2.7 to 4.5 km (1.6 to 2.8 mi) burial depth (Figure 4). Although open secondary pores after K-feldspar are rare in well 29/10-2, in other Fulmar wells, it has been observed that some secondary pores contain ankerite cement (Figure 3A), whereas others are partly surrounded by the cement, but it does not penetrate the secondary pores. A similar relationship is observed between secondary porosity and quartz overgrowths, with a minority of secondary pores containing quartz overgrowths (Figure 3B). A regional increase in quartz overgrowth abundance is also observed from about 2.5 to 5 km (1.5 to 3.1 mi) (Figure 7). The dissolution of K-feldspar and

the precipitation of ankerite and quartz are hence regarded as contemporaneous, the reactions perhaps being caused by the influx of CO₂ into the sandstone, as modeled by Barclay and Worden (2000). Assuming that these reactions occurred under open-system conditions, which would allow for an import of CO₂, then they must have occurred in a predominantly water-filled environment. Hence, the original oil charge must have leaked off by this time, i.e., by the time the Fulmar Formation was buried to 3 km (1.8 mi) depth, between 59 and 10 Ma (Figure 9). Indirect evidence suggests that the Fulmar Formation was water filled at about 30 Ma; in the Fulmar Formation cored in some Central Graben wells, but not well 29/10-2, a phase of illite growth is recorded at about 30–35 Ma (Darby et al., 1997). It could be presumed that this illite grew in a water-filled rock, and that, hence, the Fulmar Formation in well 29/10-2 was also water filled by this time.

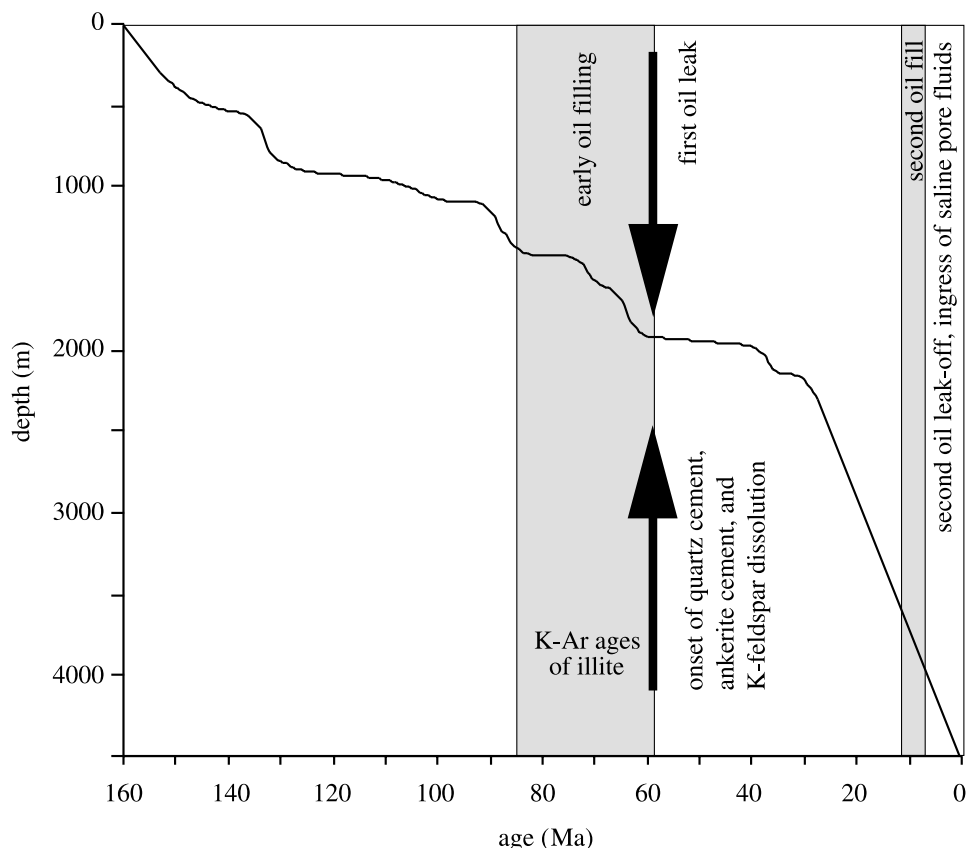
The Second Hydrocarbon Charge

Petrographic observation of thin sections provides the evidence for the presence of a second hydrocarbon charge in the Fulmar Formation during the later stages of burial. The outer rims of all the ankerite cement crystals are stained dark brown (Figure 3C), assumed to be by bitumen because it is nonluminescent in UV light. Scanning electron microscopy imaging of chip samples shows the surfaces of the ankerite crystals to be pitted because of dissolution (Figure 3D). However, the etching is only superficial, such that the crystal surfaces of the ankerite are still clearly visible. The corrosion pits in the ankerite surface are full of bitumen, hence, the brown coloration of the ankerite in thin section. Although the source of the fluids that corroded the ankerite is unknown, the texture does provide unequivocal evidence for the presence of hydrocarbon throughout the sandstone at a late stage of burial, i.e., after the cessation of growth of the ankerite. Because this hydrocarbon is not present in the reservoir at the present day, the charge must have leaked off. The second hydrocarbon charge was probably gas condensate, which migrated into several nearby fields late in their geological histories (Isaksen, 2004).

Oil Stain Proves Paleofill

The presence of bitumen in the Fulmar Formation is strong evidence for the past presence of oil (Figure 3A, B). Because the bitumen is present throughout the cored section, it is interpreted as the remains of a paleo-oil

Figure 9. The timing of the two episodes of oil filling and the major diagenetic events for well 29/10-2. Burial curve is from Darby et al. (1997).



pool. The migrating hydrocarbon is thought to move along focused pathways and not pervasively through the body of a sandstone and so cannot account for the observed distribution of bitumen and oil staining (Dem-bicki and Anderson, 1989; Catlan et al., 1992). Bitumen can form by a variety of mechanisms, e.g., by in-situ cracking of a hydrocarbon charge caused by increasing temperatures during burial (so-called thermal bitumen) or caused by the influx of a secondary gas charge causing the exsolution of bitumen, or by biodegradation (Lomando, 1992). There have been two periods in the history of well 29/10-2 when bitumen could have formed. During the initial charging with oil, the temperature of the Fulmar Formation would have been very low (about 50°C from the basin model of Darby et al., 1997) and well within the range at which biodegradation of hydrocarbon can produce bitumen. Later, as gas condensate filled the reservoir for a second time, bitumen could have been produced by interaction with the residual oil from the first charge.

From petrographic data, it is not possible to unequivocally date all of the bitumen. A minority covers quartz overgrowths, and some infills the corroded margins of ankerite and so is unequivocally late in the petro-

graphic sequence. However, most of the bitumen coats detrital grain surfaces, where it is frequently intergrown with clay coats. Little or no bitumen exists within most of the secondary pores. This could be interpreted as evidence that the bitumen predates most of the K-feldspar dissolution that generated the secondary pores, or it could simply record that it was difficult for oil (from which the bitumen was precipitated) to enter the pores through the surrounding overgrowths and clay coats. Whether most of the bitumen is from the first charge of oil or from the later charge, which was probably gas condensate (Isaksen, 2004), is, hence, difficult to determine. The lack of petrographic evidence for the early bitumen is equivocal, as above. An attempt to determine the origin of the bitumen by chemical analysis was unsuccessful because of the contamination of the core samples with oil-based drilling mud.

The Timing of the Second Leak-off

Examination of the quartz overgrowths for fluid inclusions revealed that most of the inclusions are preserved within healed fractures, which cut the detrital

quartz grains. These have a temperature range of 133–145°C (Table 4), with a modal value of 135–137°C that corresponds to ca. 4 Ma using the basin model of Darby et al. (1997). The fractured quartz grains represent a period of compaction of the reservoir, perhaps because of an overpressure release event that transferred the load of the overburden from the pore fluid to the framework grains. A possible mechanism for overpressure release is the mechanical failure of the reservoir seal, perhaps because of a change in regional stress patterns. The late-stage hydrocarbon present within the reservoir may have been lost during this overpressure release event at approximately 4 Ma (Figure 9).

Pore fluids in many Fulmar Formation sandstones are highly saline at the present day (in excess of 150,000 ppm in the nearby Puffin and Fulmar fields; Warren and Smalley, 1994; see Figure 1 for location). No data are available from well 29/10-2 concerning present-day pore-water salinities, nor is any water available as the well was abandoned after drilling. However, it seems reasonable to assume that the pore waters are highly saline. Macaulay et al. (1997) showed that high-salinity fluids had migrated vertically through the Fulmar Formation in the Fulmar field (Figure 1) and measured temperatures from aqueous fluid inclusions in the range of 85–140°C. Macaulay et al. (1997) suggested that these fluids were derived from the extensive Zechstein evaporites of Permian age, which underlie the Mesozoic rocks of the Central Graben. We suggest that highly saline pore waters, derived from the Zechstein evaporates, were driven into the Fulmar Formation at the time that seal failure occurred above the Fulmar Formation. This caused a drop in overpressure sufficient to fracture the framework quartz grains, which subsequently healed, trapping fluid inclusions. Aqueous fluid inclusions in the healed fractures have a range of salinities ranging from close to seawater to 140,000 ppm NaCl equivalent (Figure 6). The maximum-salinity fluid-inclusion measurement is the best estimate of the salinity of the present-day pore fluids in the Fulmar Formation of well 29/10-2. Figure 10 shows a summary of the major diagenetic events within the sandstone.

Pore-Water Isotopic Evolution

Figure 11 shows the evolution of the oxygen isotopic composition of the pore water for the Fulmar Formation in well 29/10-2 during burial. The curve is constrained initially by the growth of the dolomite cement. This cement, following the interpretation of thin-section textural evidence described by Hendry et al.

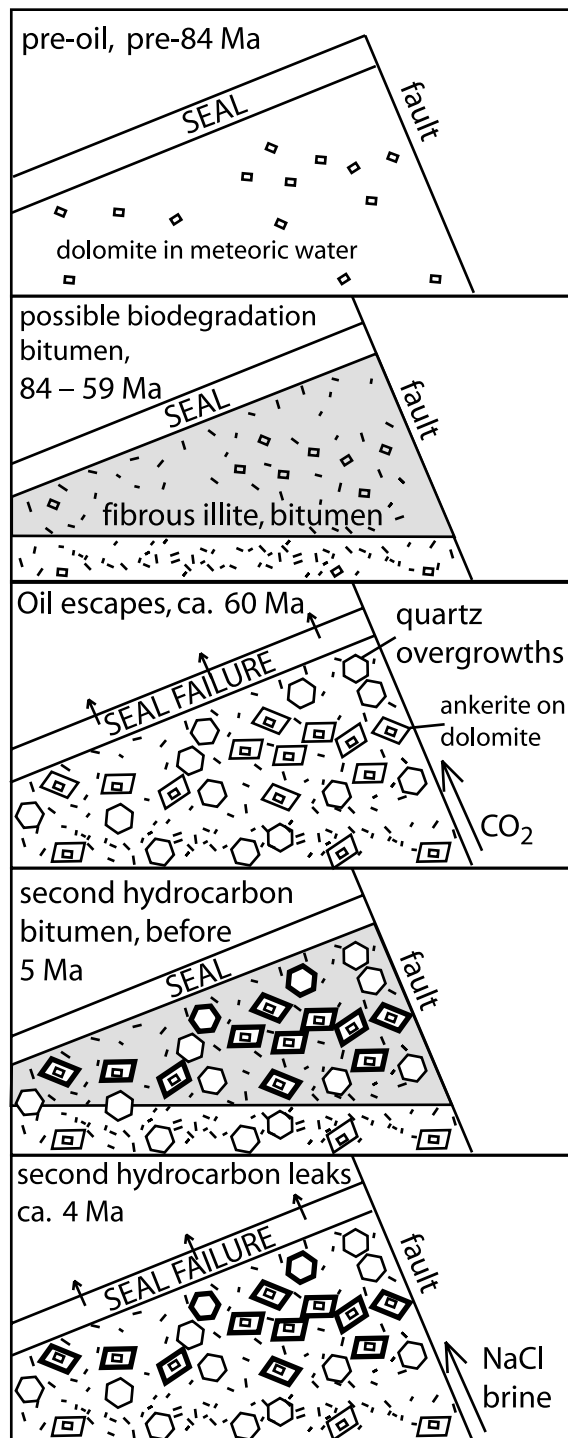
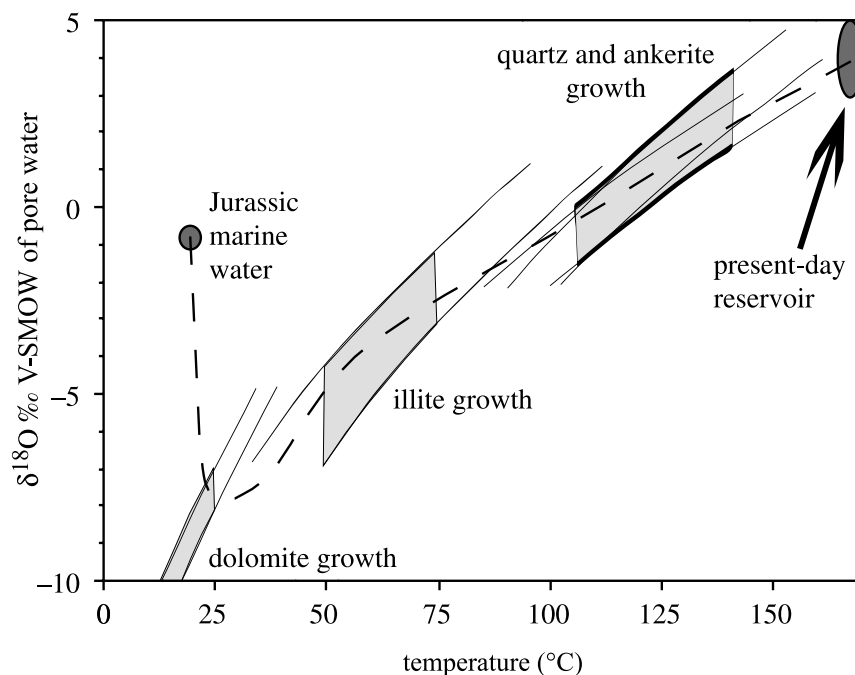


Figure 10. Summary of major events in the tilted-fault block structure into which well 29/10-2 was drilled. Cross section is diagrammatic only.

(2000b), is thought to have grown within the zone of bioturbation. So close to the sediment-water interface, temperatures would have been essentially those of the overlying seawater. Figure 11 shows that to reconcile

Figure 11. Pore-water evolution model for the Fulmar Formation in well 29/10-2, shown as the dashed line. The marine pore waters from the time of deposition were displaced by meteoric water, which slowly evolved to more ^{18}O -rich compositions. The shaded areas are conditions under which the authigenic minerals are interpreted to have grown, as constrained by stable isotope data and petrographic relationships.



the oxygen isotope data to such low temperature growth (assumed to be less than 30°C), the dolomite must have grown from pore waters of meteoric origin. Such water was presumably introduced into the shallow subsurface as part of a freshwater lens developed from land, which would have lain to the west and northwest during Fulmar Formation time.

Previous attempts to determine the extent of meteoric water flushing within the Fulmar Formation have had varying degrees of success. Wilkinson et al. (1994) tried to determine whether meteoric water ever penetrated as far as well 29/10-2 using oxygen and hydrogen stable isotope ratios of authigenic illite, but were unable to come to a firm conclusion as the hydrogen stable isotope data were thought to have been reset during burial. However, Hendry et al. (2000b) thought that the dolomite in the Franklin-Elgin area (some 25 km [15 mi] to the north) had grown from contemporary seawater. Because the Franklin-Elgin area is one of the deeper parts of the west Central Graben, it is quite possible that meteoric water did not penetrate this area, whereas meteoric water did flush the more shallow, more proximal area around well 29/10-2.

Oxygen isotopic evolution of the pore water is constrained during the next stage of burial by the oxygen isotopic ratios of authigenic illite (Figure 11). Using the K-Ar ages to estimate burial temperatures from the basin model of Darby et al. (1997) suggests the growth of illite at, or close to, 50°C . This implies growth from

pore waters of either meteoric water composition, or slightly evolved, i.e., slightly enriched in ^{18}O compared to meteoric water. In general, pore fluids in sedimentary basins evolve toward high $\delta^{18}\text{O}$ values during burial (Clayton et al., 1966).

The next stage in the pore-water evolution is constrained by both quartz overgrowth and ankerite oxygen isotopic ratios (Figure 11). The pore-water $\delta^{18}\text{O}$ -temperature curves for ankerite and quartz overgrowths apparently overlie each other in the region of interest. This is compatible with the reaction modeled by Barclay and Worden (2000), where K-feldspar dissolution is triggered by CO_2 influx, to generate quartz, ankerite, and illite. Note that the oxygen isotopic composition of ankerite used in Figure 11 is that calculated using separated samples with measured ankerite-dolomite ratios (Figure 2). Figure 5 shows that there is a minority of the ankerite with significantly lighter $\delta^{18}\text{O}$ values than this calculated end-member composition. Comparing the data from well 29/10-2 with other data from the Fulmar Formation (unpublished; Hendry et al., 2000a), it is apparent that the low $\delta^{18}\text{O}$ ankerite in well 29/10-2 is anomalous. The significance of this unusual ankerite is unknown, although anomalously light $\delta^{18}\text{O}$ values have been reported in many studies of diagenetic carbonates (Mozley and Burns, 1993).

The isotopic composition of the present-day pore water in well 29/10-2 cannot be measured because samples are not available. The nearest available pore-water

samples from the Fulmar Formation are from the nearby Franklin field ($\delta^{18}\text{O} = 4.2\text{‰}$ V-SMOW; Table 5), the Ula field ($\delta^{18}\text{O} = 3.3\text{‰}$ V-SMOW; Warren and Smalley, 1994), and the Fulmar field ($\delta^{18}\text{O} = 4.2 \pm 0.2\text{‰}$ V-SMOW; Macaulay et al., 1997). Based on these analyses, we suggest that the present-day pore water in the Fulmar Formation in well 29/10-2 will have a $\delta^{18}\text{O}$ value within the range 3–5‰ V-SMOW (Figure 11). This enables an endpoint to be plotted on the pore-water evolution curve in Figure 10.

The Paleofield

If explorationists had drilled well 29/10-2 before the seal ruptured, what would they have found? Most of the nearby fields contain gas condensate (e.g., Lasocki et al., 1999), although oil is also present in the area. Hydrocarbon staining of clays and bitumen is found throughout the cored interval (13,745–14,452-ft [4190–4405-m] driller's depth) and is presumably present in the uncored interval above to the top of the Fulmar Formation at 13,660 ft (4164 m). This equates to a hydrocarbon column of 241 m (790 ft). It is unknown whether the hydrocarbons extend down into the underlying Pentland Formation, which, in other fields, can be a reservoir horizon. Such large hydrocarbon columns are by no means unusual in the area; Lasocki et al. (1999) records a condensate column of 525 m (1722 ft) in the nearby Franklin field. The seal in all cases is a combination of the overlying Heather Formation, which has a transitional contact with the Fulmar Formation and grades upward from fine sandstone to siltstone; the Kimmeridge Clay, a claystone; and Lower Cretaceous shales that predate chalk deposition. As exploration ceased once the well was found to be dry, it is not possible to estimate the reserves that the field may once have held, although other Fulmar Formation fields in the area are in the range of 120–245 million bbl of condensate and 820–890 MMSCF of gas (Lasocki et al., 1999).

CONCLUSIONS

Diagenetic minerals and petrography can be used to elucidate the hydrocarbon history of a reservoir sandstone, even when the history involved multiple phases of hydrocarbon charging and leak-off. The Fulmar Formation in well 29/10-2 has had a complex history of hydrocarbon charging, with at least two phases of hydrocarbon filling and two phases of emptying (Figure 10). The diagenetic history of the Fulmar For-

mation is more complex than has previously been realized because of the interaction between inorganic diagenetic reactions and hydrocarbon. Previous work had suggested that all diagenesis predated hydrocarbon charging.

Hydrocarbon charging began in the Fulmar Formation in well 29/10-2 about 85 Ma, when the sandstone was at a modeled temperature of only 50°C (Figures 9, 10). At least 25 m.y. were required to fill a 200-m (660-ft) oil column (Figure 8). Authigenic fibrous illite grew during charging, despite the low temperatures. Pore-water salinities were low (probably below seawater values) because of the effects of meteoric water flushing close to the paleoshoreline (Figure 11).

The reservoir subsequently emptied of hydrocarbon, presumably because of seal failure (Figures 9, 10). The exact timing is uncertain, but was perhaps 60 Ma. Diagenetic reactions, including K-feldspar dissolution and the precipitation of ankerite and quartz overgrowths, then occurred in an open system, which allowed for CO₂ import. A second phase of authigenic illite grew, but has not been dated in this well, although it has been dated in other wells within the Central Graben.

A change in pore fluids in the sandstone resulted in the superficial corrosion of ankerite crystals, where previously, they had been growing. A second charge of hydrocarbon entered the reservoir, probably gas condensate, and filled the resulting microporosity at the edges of the authigenic ankerite grains with bitumen (Figures 9, 10). The gas condensate subsequently leaked off (as the reservoir is full of water at the present day), probably because of seal failure coincident with a period of overpressure release that caused fracturing of quartz framework grains at 4 Ma. Fluid inclusions within the healed quartz grains record some high salinities, which are typical of the pore fluids of the present-day Central Graben. These pore fluids were probably derived by vertical migration of fluids from the underlying Permian Zechstein evaporates during the leakage of overpressure.

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