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Synchronous Oil Migration and Cementation in Sandstone Reservoirs Demonstrated by Quantitative Description of Diagenesis [and Discussion]

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Synchronous oil migration and cementation in sandstone reservoirs demonstrated by quantitative description of diagenesis

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We present a model that explains the patterns of sandstone burial diagenesis in certain oil reservoirs, in which petroleum migration and burial cementation were synchronous. The coincidence of these two processes controls the chemistry and distribution of major burial cement phases across the field, which in turn controls the distribution of reservoir quality, causing a rapid decline of porosity and permeability with depth. Such a rapid poroperm deterioration is observed in many North Sea sandstone oilfields; we highlight the Magnus Sandstone Member of the Magnus Oilfield, northern North Sea as a type example of such a reservoir.

The two most significant elements of the synchronous cementation and migration model are that burial cementation in the reservoir occurs over a restricted time interval, probably less than 10 Ma and that rapid and widespread fluid circulation is not invoked to explain the concentrations of cements observed. We speculate that cementation takes place at, and in a series of zones below, the oil–water contact which descends as oil fills the reservoir, with little change to the bulk chemistry of the reservoir formation waters through time.

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1. Introduction

Porosity–depth trends for Mesozoic and Cenozoic sandstones in the North Sea show an overall porosity decline with increasing depth. Across the range of burial depths at which North Sea petroleum reservoirs are usually found (*ca.* 1.5–5.5 km), the porosity loss ranges from 6% per km (Bjørlykke *et al.* 1989), through 7% per km (BP data, northern North Sea sandstones), up to 9% per km (Selley 1978; Bjørlykke *et al.* 1989), with an overall 'North Sea sandstone' porosity loss gradient of about 8% per km. While this regional trend is of some use in predicting porosity in undrilled sandstone prospects, it masks several interesting features which relate to porosity decline within individual fields (Gluyas *et al.*, unpublished work). Firstly, there appear to be a set of oilfields whose porosities fall at or near values predicted by sandstone compaction curves (Baldwin & Butler 1985). These fields are almost exclusively Cenozoic deepwater sandstones (figure 1). Another set of fields show a porosity decline with depth which roughly parallels the regional porosity loss trend, but displaced to lower porosities. These reservoirs comprise Mesozoic marine and marginal marine sandstones. A third set of fields show a very rapid loss of porosity (and permeability) with depth, up to 20% porosity loss per km, but whose crestal porosities correspond closely to porosities that would be predicted by sandstone

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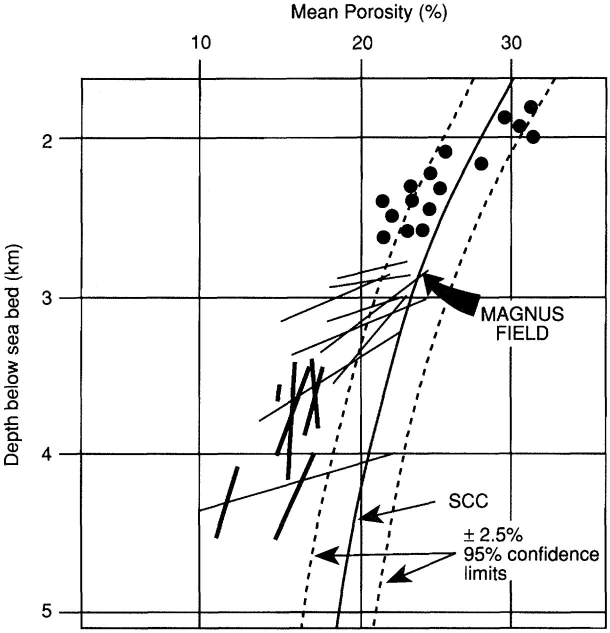

Figure 1. Porosity–depth plot for North Sea sandstone reservoirs. Solid circles represent Cenozoic deepwater sandstone reservoirs and plot at, or very close to, compaction curve porosities of Baldwin & Butler (1985). Solid lines represent best-fit lines for porosity–depth trends from individual North Sea fields, of Mesozoic marine or marginal marine origin. The best-fit lines were constructed from fields with three or more well-derived porosity–depth points, and are not extrapolated beyond maximum or minimum porosities recorded in the fields. Note that the fields showing rapid porosity loss with depth commonly intersect porosities predicted from standard compaction curves (SCC, with ±95% confidence limits) at their crests, and are represented by thin solid lines. The Magnus Oilfield porosity–depth trend is arrowed.

compaction curves (figure 1). These fields are also of Mesozoic marine and marginal marine origin. It is the rapid deterioration of reservoir quality in these sandstones that is the focus of this paper. In a few cases, it is clear that facies changes can explain or partially explain the dramatic loss in porosity and permeability, but in most cases changes in the extent of diagenesis appear to be responsible for the decreasing quality of reservoir. We illustrate this with a well-constrained example of an oilfield for which we have produced a detailed quantitative diagenetic history which links burial diagenetic modification of the sandstone to petroleum migration into the reservoir. Note that in this analysis, we do not consider the effects of *significant* overpressure in porosity preservation; the subject of overpressure and sandstone reservoir quality is covered in more detail by Ramm (1991, 1992).

2. The geology of the Magnus Oilfield

This study focusses on the Magnus Oilfield in the northern North Sea (De'Ath & Schuyleman 1981; Rainey 1987; Emery *et al.* 1990; Shepherd 1991; Macaulay *et al.* 1992), which lies 160 km north east of Shetland (figure 2). The main reservoir of the field, the Magnus Sandstone Member, comprises *ca.* 100 m thickness of Upper Jurassic (Kimmeridgian) submarine fan sandstones, over- and underlain by Kimmeridge Clay Formation mudstones. Magnus is a tilted fault block trap, topsealed mainly by Kimmeridge Clay mudstones and also by Cretaceous marls

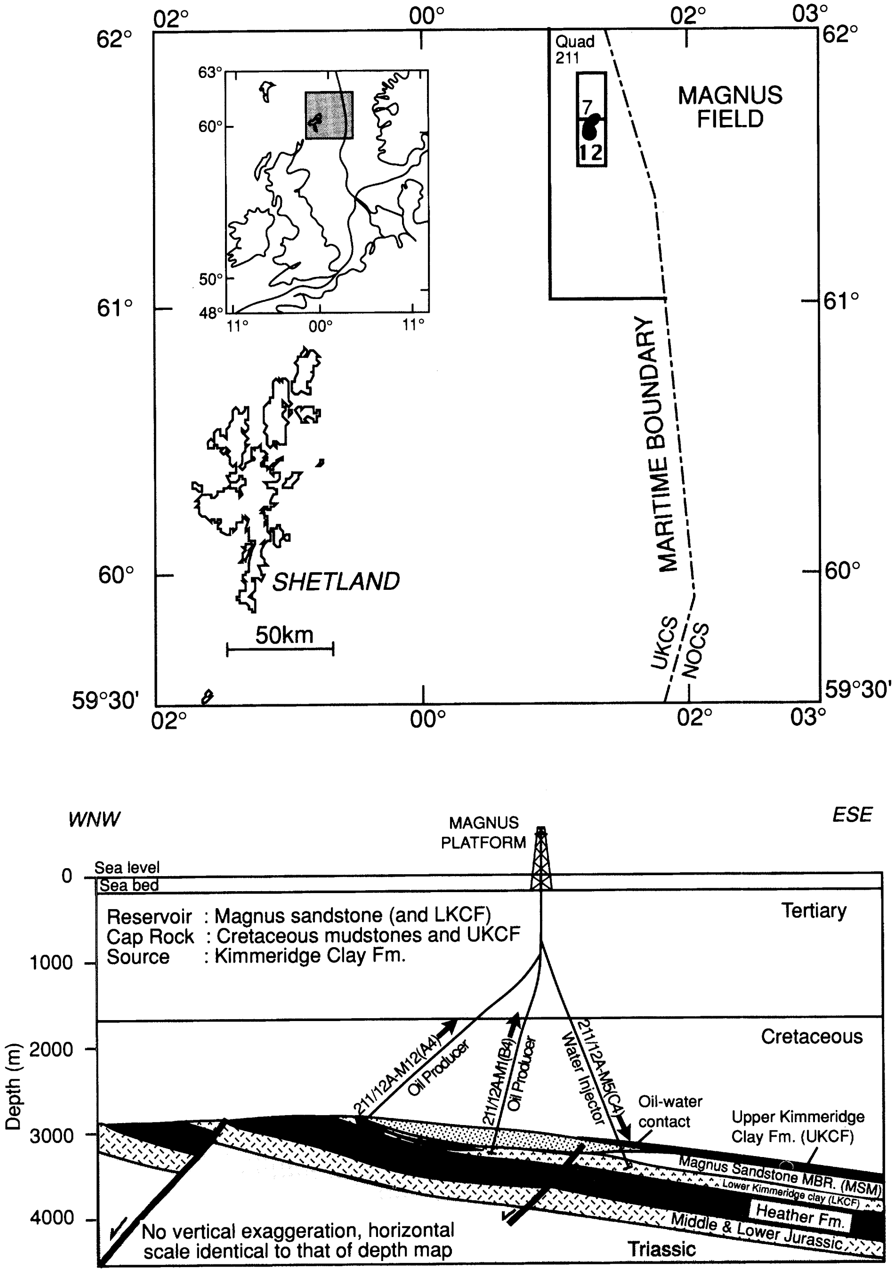

Figure 2. Location of the Magnus Oilfield, northern North Sea, and general geological cross section.

above the ‘base Cretaceous’ unconformity at the crest of the field (figure 2). The oil in the Magnus Sandstone Member was sourced from the Kimmeridge Clay Formation, several km downflank of the Magnus Field; the Kimmeridge Clay of the Field is not mature at reservoir depths.

The porosity decline in the field is *ca.* 17% porosity loss per km, significantly greater than regional porosity–depth gradients (figure 1). Permeability decline is also significant, ranging from several hundred millidarcies at the crest to a very few tens of millidarcies downflank, particularly in the aquifer adjacent to the oil–water contact. The poor reservoir quality in the aquifer has resulted in a production strategy whereby seawater is injected directly into the oil leg, not into the aquifer (Heaviside *et al.* 1983).

3. Early diagenesis

Early diagenesis of Magnus sandstones comprised limited non-ferroan calcite and pyrite precipitation during and shortly after deposition (Rainey 1987). The calcite cemented intervals are generally a few to several cm thick, and locally comprise up to, and in excess of, 40% calcite. Sandstone cemented by the calcite contains no diagenetic phases other than pyrite, and the presence of feldspars unaltered by subsequent diagenesis along with the high pre-calcite porosity suggests early precipitation of the calcite, probably shortly after deposition. Pyrite occurs as dispersed framboids throughout the Magnus sandstone, with overall concentrations of less than 1% rock volume, although in a single well at the crest of the field, pyrite concentrations increase to 10% rock volume. The framboidal form of the pyrite, and its presence within calcite nodules also suggests it was an early diagenetic phase.

The next episode of diagenesis occurred when the Magnus sandstones were subaerially exposed during the Early Cretaceous, at which time meteoric water penetrated the unit, causing potassium feldspar dissolution and kaolinite precipitation at the crest of the field (Emery *et al.* 1990). Locally, porosity enhancement of up to 5% has been achieved by feldspar dissolution; however, this enhanced porosity is only of significance to depths of about 10 m below the ‘base Cretaceous’ unconformity. Meteoric water flushing was *not* responsible for fieldwide porosity modification. All subsequent burial diagenesis of the Magnus sandstones could have occurred in a derived version of this Cretaceous meteoric water which is still recognizable in present Magnus formation waters. These waters have salinites approximately half that of seawater, despite 130 Ma of diagenetic reaction. There has apparently not been significant flushing of this Cretaceous meteoric water from the Magnus Field, which might be expected if multiple (tens of thousands of) pore volumes of water had been circulated through the Magnus system during burial diagenesis.

4. Burial diagenesis

Following Cretaceous meteoric water penetration and associated diagenesis, the Magnus sandstones became buried beneath later Cretaceous sediments and were modified by compaction, with little or no diagenetic reaction for about 40 Ma. At about 80 Ma, however, thermal modelling of the Kimmeridge Clay source rock down dip from the Magnus Field indicates that the first low maturity oil reached the Magnus sandstones and this coincided with the beginning of burial cementation. Magnus burial cements comprise, in approximate paragenetic sequence, feldspar overgrowths, quartz overgrowths, kaolinite, illite, siderite and ankerite. From petrographic observations, we can be sure that the order feldspar–quartz–ankerite is correct, but the relative timing of the clay minerals and siderite remain ambiguous; they probably overlap.

The earliest burial cement, feldspar overgrowths, are volumetrically minor (less than 1% rock volume), and do not contribute to the steep porosity gradient within the field. These cements contain primary aqueous fluid inclusions and primary inclusions containing low maturity (yellow fluorescing) petroleum (figure 3). The

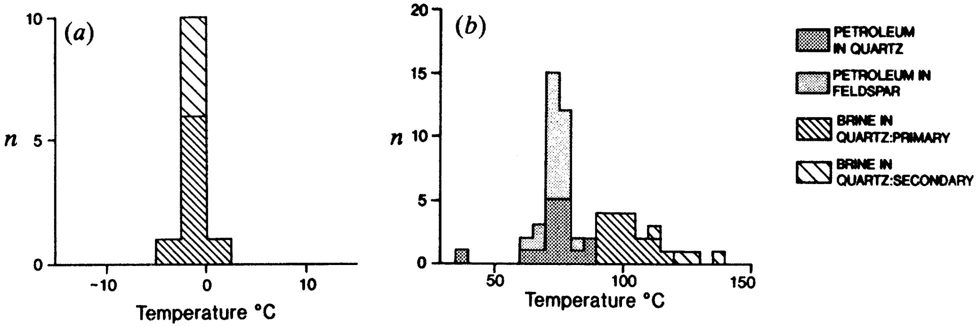

Figure 3. Fluid inclusion ice final melting temperatures (*a*) and homogenization temperatures (*b*) from quartz and feldspar cements, Magnus Field.

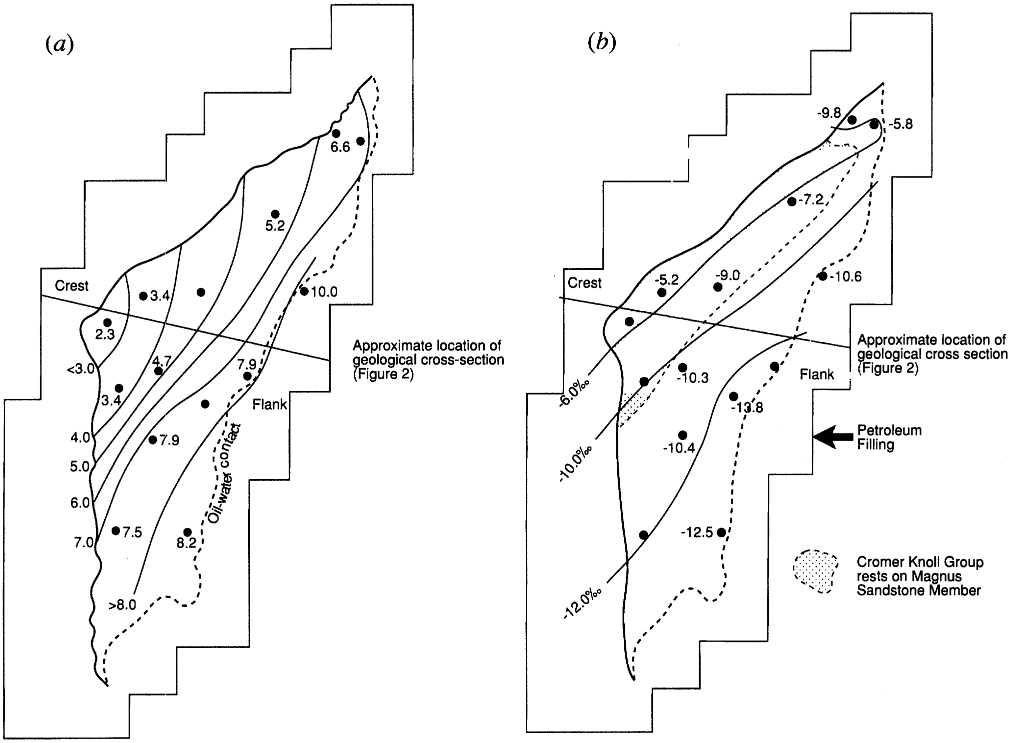

Figure 4. (*a*) Quartz cement distribution, as % rock volume, in sandstones of the Magnus Field. (*b*) Carbon isotopic compositions of ankerites in sandstones of the Magnus Field.

following cement, quartz, is the most volumetrically significant diagenetic phase in Magnus and is the main cause of porosity decline across the field. It is not uniformly distributed across Magnus, forming about 2% rock volume (and possibly less) at the crest of field, yet greater than 8% rock volume at the flanks (figure 4*a*). However, the quartz cement appears to be petrographically and geochemically uniform across Magnus. Quartz overgrowths sampled in detail from three widely spaced wells were unzoned or weakly zoned in cathodoluminescence and contain both aqueous and petroleum primary fluid inclusions (figure 3). The aqueous fluid inclusions have a relatively restricted range of homogenization temperatures, which, when converted to a *maximum* time range for quartz precipitation from Magnus burial history

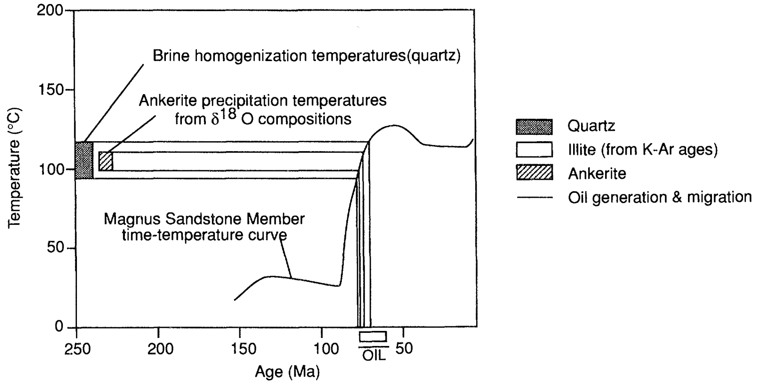

Figure 5. Burial and thermal history of the Magnus Sandstone Member, showing timing of different burial diagenetic episodes, and the timing of oil generation and migration from Kimmeridge Clay source rocks.

Table 1. *Illite ages*

well	depth/MBRT	age/Ma
211/12a-11	3144.60	67.7 ± 2.1
211/12a-11	3178.98	87.7 ± 2.5
211/12a-11	3195.90	71.9 ± 2.5
211/12a-11	3203.63	62.6 ± 2.2
211/12a-11	3222.77	64.0 ± 1.6

curves, yield an age range of 80–65 Ma (figure 5). The aqueous fluid inclusions in the quartz also yield final melting point temperatures which convert to salinities between fresh- and seawater very similar to those of present-day Magnus formation water. This important result means that during and since quartz precipitation there is no evidence that Magnus waters have ever been different from a modified version of the Cretaceous meteoric water. Petroleum fluid inclusions in the quartz cement are of slightly higher maturity (blue-green fluorescing) than those in the petrographically earlier feldspar, indicating progressive maturation of the source rock during burial cementation (figure 3).

The next burial diagenetic phase for which we have geochemical information is illite. Authigenic fibrous illite is of relatively minor volumetric importance in Magnus, forming less than 1 % rock volume on average and showing no systematic spatial variation across the field, unlike quartz. Illite was dated directly using K–Ar systematics as described by Lee *et al.* (1985) and Hamilton *et al.* (1989). Following careful magnetic separation, Magnus illites yielded a K–Ar age range of 87–62 Ma from five samples, overlapping with the age range for quartz burial cementation, and giving a mean age of 70.8 ± 9 (σ) Ma (table 1). If the oldest sample, which gives an age of 87.7 Ma, is ignored, then the mean age of illite precipitation from the remaining four samples is reduced to 66.6 ± 3.6 (σ) Ma. This procedure is probably reasonable because the 87.7 Ma sample is distinctly older (at least 16 Ma) than the remaining four, and is most likely to have been contaminated by older, detrital material.

The final major burial diagenetic phase in Magnus was ankerite, forming on average 4 % rock volume, and, like illite, showing no systematic spatial distribution across the field. Isotopic analysis of 40 samples of ankerite from 10 wells across the field yielded oxygen isotope compositions (table 2) which displayed very little

Table 2. *Stable isotopic compositions of ankerites and formation waters*

ankerites well	depth/mBRT	$\delta^{18}O$ (‰, PDB)	$\delta^{13}C$ (‰, PDB)
211/12-2	3237.75	−10.14	−10.36
211/12-2	3287.75	−9.87	−9.78
211/12-2	3298.25	−10.99	−11.75
211/12-5	3083.50	−9.81	−10.63
211/12-5	3162.50	−10.99	−10.47
211/12-5	3176.50	−10.57	−10.52
211/12-6	3033.00	−9.05	−7.32
211/12-6	3044.25	−9.18	−7.04
211/12a-11	3178.02	−10.36	−12.69
211/12a-11	3193.00	−10.09	−12.32
211/12a-11	3205.00	−10.31	−12.44
211/12a-M1	3271.86	−11.08	−11.37
211/12a-M1	3271.96	−10.96	−10.62
211/12a-M6	3390.25	−10.83	−10.21
211/12a-M6	3412.45	−9.49	−7.59
211/12a-M6	3428.99	−8.70	−8.82
211/12a-M8Z	3369.25	−9.55	−13.82
211/12a-M10	3644.00	−10.19	−5.23
211/12a-M10	3644.00	−10.14	−5.35
211/12a-M12	3766.50	−9.26	−8.40
211/12a-M12	3769.49	−10.28	−10.00
211/7-1	3199.00	−9.41	−10.09
211/7-1	3214.00	−8.93	−9.55
211/7a-3	3101.75	−10.02	−10.31
211/7a-3	3105.75	−9.42	−6.11
211/7a-3	3107.25	−9.58	−6.19
211/7a-3	3108.59	−9.55	−5.06
211/7a-3	3110.78	−9.31	−5.05
Mean $\delta^{18}O$ of 28 samples is		−9.93	with a standard deviation of 0.66.

formation waters	$\delta^{18}O$ (‰, SMOW)	
211/12a-M7	2.08	
211/12a-M7	0.95	
211/12a-M7	1.81	
211/12a-M7	1.58	
211/12a-M7	1.61	
211/12a-M7	1.75	
211/12a-M7	1.98	
Mean $\delta^{18}O$ of 7 samples is	1.68	with a standard deviation of 0.34.

variation, suggesting that ankerite precipitated over a restricted temperature and time interval, like the quartz and illite. To determine the absolute temperature of ankerite precipitation from a fractionation equation, an assumption about the water oxygen isotope composition must be made. We assumed that the water which precipitated the ankerite is the same as present Magnus formation water, produced from the oil zone, whose oxygen isotopic composition has been determined (table 2). This assumption is based on our observation that the Magnus formation water remained largely unchanged from quartz cementation to the present time. From

Friedman & O'Neil's (1977) fractionation equation, the temperature range of ankerite precipitation is 103–113 °C, corresponding to a time of 75–60 Ma (figure 5), and once again, coincident with precipitation of the other burial cements.

The carbon isotopic results from the ankerites were much more variable than oxygen (table 2), and showed a systematic variation across the field (figure 4*b*). This trend suggests a mixing of different carbon sources which ultimately became incorporated in ankerite. One carbon source comprised bicarbonate with $\delta^{13}C$ compositions of *ca*. 2‰, derived from Cromer Knoll Group nodular chalks overlying the Magnus sandstone at the crest of the Field. The other carbon source is interpreted to have comprised bicarbonate with $\delta^{13}C$ compositions of −15‰ to −25‰, which ultimately derived from organic matter, probably from the Kimmeridge Clay source rocks, just before and during oil migration.

5. Discussion

From the foregoing description and timing of Magnus burial diagenesis, we recognized six features which must be reconciled in any overall burial diagenetic model for Magnus: (i) The late stage, and limited time interval available for, precipitation of burial cements. (ii) The characteristic petrographic sequence of cements at any one point yet their coincident apparent ages as deduced from direct geochemical dating, oxygen isotopes and fluid inclusions. (iii) The coincidence of oil migration and cementation, as evidenced directly by primary petroleum inclusions in the framework silicates, and indirectly by the carbon isotopic composition of the ankerites. (iv) The spatial variation of quartz cements but *not* of illite or ankerite. (v) The change from silicate to carbonate precipitation at a very late stage. (vi) The apparently unchanging formation water during and after burial diagenesis.

All these features can be explained by proposing a direct link between oil migration and diagenesis, which, in the case of Magnus, were both of similar duration (10–15 Ma). In general, as oil migration proceeds from source rock to reservoir, the buoyant oil will initially accumulate at the crest of a structure, and will tend to migrate there along the paths of least resistance, rocks with the lowest pore entry pressures, as a series of filaments (England *et al.* 1987). This filling process leads to a very diffuse oil–water contact, and any one pore in this diffuse zone may change its oil saturation many thousands of times before reaching its final saturation state. Petroleum droplets can hence be included as fluid inclusions within growing diagenetic phases during this time, and as Walderhaug (1990) and Ramm (1992) point out, chemical diagenesis in the form of cementation and pressure dissolution will tend to continue within reservoirs until very high oil saturations are reached. The descent of this diffuse oil–water contact and series of diagenetic 'zones' beneath the contact may have controlled the distribution, petrography, timing and silicate–ankerite flip-over. This model is illustrated schematically in figure 6. At time t_1, *ca*. 75–80 Ma, the crest of the field, A, would have been a highly oil saturated zone, having experienced a limited amount of quartz cementation, followed by illite, then by ankerite precipitation. Petroleum migration into the reservoir would then have reduced water saturations to such low levels in the reservoir that diagenesis would have largely ceased. The carbon isotopic composition of the latest diagenetic ankerite will have been dominated by the main source of carbon in the formation water at the crest of the structure adjacent to Cromer Knoll Group carbonates, giving a more positive carbon isotopic signature. At position B, time t_1, only quartz cementation

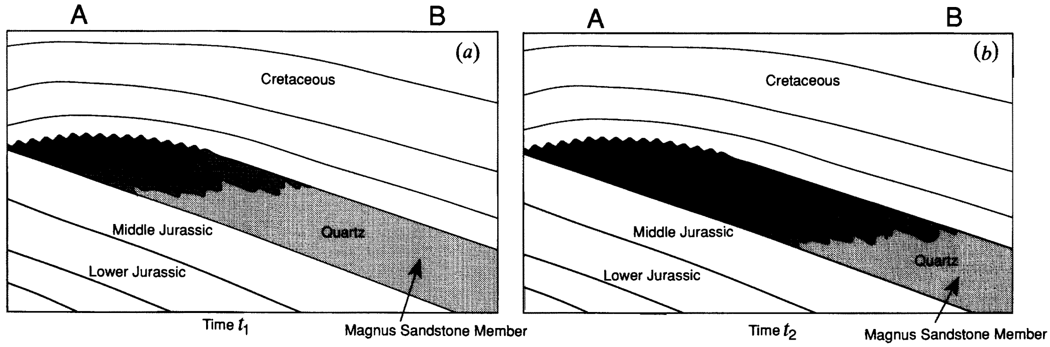

Figure 6. Model for Magnus burial diagenesis. See text for details.

will be occurring, but this will be synchronous with the precipitation of other diagenetic phases in the reservoir (e.g. at position A) and with oil migration. At time t_2, *ca.* 65–70 Ma, the oil–water contact will have descended further, halting diagenesis at A and B. B will have received a large quantity of quartz cement as the oil–water contact descended between *ca.* 80 and 70 Ma, but will have received approximately the same amount of illite and ankerite as at A, because of the invariant size of the illite and ankerite diagenetic zones. The ankerite at B will have received the bulk of its carbon from organic matter in maturing Kimmeridge Clay Formation source rocks, giving the ankerite a more negative isotopic signature.

It is difficult to invoke large quantities of circulating fluids to have transported the burial diagenetic components into Magnus (see also Macauly *et al.* 1992), given our dual constraints of unchanging formation water during and after burial diagenesis and the two-component carbon mixing evidenced by the ankerite. In the absence of rapid fluid circulation for cementation, it is possible that organic acids associated with source rock maturation may have been the agents of silica transport, but some evidence of these waters should remain in the reservoir fluids today as the presence of solute complexation would probably have modified the formation water composition. The importance of some organic matter involvement in burial diagenesis is implied by the carbon isotope evidence of the ankerite, but this input need not necessarily have affected the formation water composition. As suggested by our model (figure 6) much of the late-stage ankerite observed within Magnus is a record of the descent of the oil water contact. Other workers have observed high concentrations of ferroan carbonate at oil–water contacts at the present-day (Burley *et al.* 1989), yet the mechanism of preferential carbonate precipitation at oil-water contacts remains obscure.

An alternative hypothesis, invoked by Houseknecht (1988) and more recently by Ramm (1992) for quartz cementation, is that silica is supplied internally by pressure dissolution at grain–grain contacts within the sandstone. Ramm (1992) suggests that this process predominates at burial depths between 2.5–3 and 4.0 km, which are appropriate to the Magnus Field as it underwent burial diagenesis. Although this hypothesis is attractive, there are two lines of evidence which may militate against it. Firstly, pressure dissolution at grain–grain contacts in Magnus appears to have occurred on a limited scale only. The majority of the apparently sutured contacts between grains are compromise boundaries between growing quartz cement crystals. This does not, however, mean that pressure dissolution of Magnus sandstones may not have occurred down dip of the present Magnus Field. Secondly, Gluyas &

Coleman (1992) have shown that a net import of silica to the Magnus sandstones can be demonstrated by comparing the bulk chemistry of burial diagenetically altered sandstones to sandstones preserved in early non-ferroan calcite concretions which have not experienced burial cementation.

6. Conclusions

Our model of a descending oil–water contact and associated diagenetic zones beneath explains the geochemistry and distribution of major burial silicate and carbonate phases in the Magnus reservoir. This model is based on a detailed description of the distribution of diagenetic phases, their geochemical composition and the thermal history of the Magnus reservoir. The precise mechanisms for extensive burial cementation remain poorly or partially understood. In this example, it appears that reservoir formation water does not need to be replaced to encourage diagenesis, not does prolonged flushing by burial fluids appear to be applicable. However, the coincidence of petroleum migration and major burial diagenesis is well demonstrated by the Magnus example, and whether or not it implies any causal relationship, it is clearly responsible for the rapid deterioration of reservoir quality observed in Magnus and probably many North Sea (and other) sandstone fields.

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Discussion

K. V. Ragnarsdottir. There is experimental evidence for large increases in Si and Al in contact with organics; therefore, it is no coincidence that elements and hydrocarbons are transported together.

P. Aagaard. You can use a general compaction trend but porosity decrease relates to cementation, deep burial and hydrocarbon filling. Is there any evidence from oil-free sandstones?

D. Emery. We need a basin with no source rocks and low organic matter to check cementation!

A. Halliday. If the interface migrated in a short time (10 Ma). Why then are illite ages the same at different depths?

D. Emery. I was only able to look at one well! K–Ar dating has poor resolution and we would like to take samples from both crest and flank and then compare.

A. Halliday. K–Ar should resolve down to 0.1 Ma.

D. Emery. Assuming perfect separation and no contamination.

M. L. Coleman. Is there any causal relationship between ankerite and its proximity to mudrocks?

D. Emery. Reducing conditions at the base of the oil column and organic matter in sediments should both influence ankerite precipitation.

M. L. Coleman. Is there much Fe in the non-muddy parts of the sandstone? Is there any local ferric oxide available for reduction?

D. Emery. Pyrite, lithics and mica are present but no significant iron in the sandstone.

R. Petrovich. I have three comments. First this is a very impressive study, a study of the type that should be coming out of oil companies. Second, it is worth noting that Professor Fuchtbauer published several papers around 1970 in which he argued in favour of the export of silica from petroleum source rocks, though he did not have the evidence that you have now obtained. Third, the amount of silica that had to be transported may well be explained by the formation of silicon-organic complexes such as have been studied by Siegel, Bennett and Marley.