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Sandstone cementation and fluids in hydrocarbon basins

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Abstract

Are porewater flow or stasis exclusive hypotheses? We think there is an intermediate view. Processes governing sandstone cementation in the deep sub-surface are elusive, case-specific and difficult to model in general terms. Combining techniques from petrography, isotopic and ion microprobe analyses with basin modelling one can narrow the possibilities towards unique hypotheses. Examples are given, predominantly from the North Sea basins, where palaeo-porewaters in different settings may evidence: (1) meteoric, compaction, or convection origins; (2) overpressured vertical leakoff; and (3) stasis and >100 m 'diffusion', helped by flow dispersion. Geochemical interaction transfers K and Al to muds, C to sands and forms secondary porosity by feldspar loss at depth, late carbonates, and hairy illite that can date oil charge. © 2000 Elsevier Science B.V. All rights reserved.

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1. Fluid motion or stasis in basins

Two main goals have driven studies of sandstone cementation in the past ten years: Firstly, the economic motive to predict porosity and permeability in hydrocarbon fields. Secondly, the academics motive to understand the motion or stasis of porefluids and the scale of mass-transport to form cements.

The study of porefluids has been marked by a remarkable fix in the viewpoints proposed by different research groups with little apparent resolution. However, new technological advances continue to drive a persistent slow progress. Computation linked to basin models has started to enable prediction of quartz cement volumes, fluid flows and oil charge timing. Micro-analytical technology enables the analysis of isotopic sub-zones within cements. Porewater can be extracted and analysed from the subsurface and micro-samples extracted from laboratory core. Desktop computers can enable the combination and analysis of data sets large enough to be statistically significant.

The variability and range of natural cementation patterns in sandstones means that it is difficult to make statistically valid assessments of the volume of minerals present. This has led to divergences between much industry practise—data-rich, cautious or under-interpretation; and academic practise—data-poor and prone to over-interpretation. This paper will lie closer inevitably to over-interpretation.

To advance our conceptual and quantitative understanding of processes—and hence our predictive ability, studies of sandstone cementation need to: date

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when cementation occurred, quantify cement volumes, identify and track sources of solute complexes supplying those cements and reconstruct palaeo-porewaters to ascertain if stasis, diffusion or advection factors influence rates of supply. Not all of these problems are tractable equally.

2. Depositional composition

In spite of the emphasis on this and other meetings on palaeo-fluids, it is apparent that the primary and first-order control on sandstone reservoir quality is depositional. This is expressed most basically as the grain-size and sorting (Beard and Weyl, 1973; Pittman and Larese, 1991; Bryant et al., 1993), which can be pragmatically mapped as depositional facies. The second factor is the mineralogical mix of the sand, which controls the reactants entering into the burial diagenetic system. On a regional basis, this is successfully used by Exxon to empirically predict cementation occurrence with depth (Paxton and Stone, 1999). But this approach needs large systematically collected commercial data sets, which remain confidential. In a related way, BP use an approach that combines predictions of grain-size and compaction with averaged quartz cementation loss of porosity adjusted to a case-by-case basis (Smalley et al., 1998).

3. Palaeo-fluids and cement supply

It is a remarkable feature of studies of ancient fluids in sedimentary basins by different research communities that models are produced that appear to favour conflicting or exclusive models for fluid behaviour in their local basins.

North American workers have produced many concepts relating to regional patterns of fluid flow (Bethke and Marshak, 1990; Garven et al., 1993). In this view, the migrating waters are considered, by some, to transport advectively cementing species—for example shallow depth quartz cementation in the USA Gulf (Lynch, 1996).

Seemingly at the opposed viewpoint, many workers in the North Sea agree about meteoric flux during shallow burial, but consider the deeper sandstones to be systems closed to fluid flow or mass-transfer, with the sediment subsiding through a density-layered porewater (Bjorlykke, 1995; Bjorkum et al., 1998). In this worldview, cementation is controlled by re-equilibration of depositional mineralogy in the depositional sand mix to increasing pressure and temperature (Aagaard et al., 1990).

Between these possibilities, other workers have shown that palaeo-fluids may expel faults advecting cements (Gaupp et al., 1993; Clauer et al., 1996), which may be static with locally supplied cements (Macaulay et al., 1992), or may migrate laterally and mix (Coleman 1999).

Case studies will be examined now at different size scales to show how combined and integrated techniques can provide insights into palaeo-fluids and mass-transfer.

4. Compaction fluid: porosity preservation, oil and quartz cement

Compilations by BP of porosity data measured from core plugs in the North Sea oilfields show that average sandstone porosity decreases with deeper burial (Emery et al., 1993). A bimodal distribution is present with two gradients of porosity decrease occurring. One is sub-parallel to the compaction curve at about 8%/km. Another much more rapid at 30–80%/km. The two gradients show no depth-related distribution in oilfields. What controls this pattern?

The Miller and Kingfisher oilfields are in the Upper Jurassic gravity-flow sandstones from the Brae depositional system at the western edge of the Viking Graben. The fields are adjacent, at similar depths of 4 km, but basin modelling shows that hydrocarbons have charged the two structures at different times from 60–10 Ma. This gives us the opportunity to examine very similar sands at different stages of diagenetic history.

Miller shows exceptional porosity at its crest and normal porosity in the water zone (24–12%). This is balanced by a rapid downward increase in quartz cement from 4 to 16%. Oil charge has been suggested to a halt or slow down of quartz cementation (Emery et al., 1993; Gluyas et al., 1993; Worden et al., 1998). The Miller data are consistent with a progressive and slow oil charge gradually slowing quartz cementation. Vertical profiles of fluid-inclusions show that to the present-day ancient fluids have not changed in salinity. The distributions of quartz cement and porosity are controlled closely by the oilfield structural elevation. Rapid porosity decline in this oilfield is caused by slow oil charge with simultaneous extended cementation (Marchand et al., 2000).

Kingfisher field has a lower reservoir in the Miller and South Brae petroleum system; this lower sand has normal porosity, with abundant quartz cement, a slow rate of vertical porosity decline and moulds of dissolved sponge spicules. The lower sand cemented before recent rapid oil charge. The same field also has an upper reservoir in a different (North Brae) petroleum system. The upper sand contains minimal quartz cement, but in contrast preserves an exceptional variety of siliceous sponge spicules. Basin modelling shows that the upper reservoir charged earlier, before the sand had heated to 80°C, when cementation started.

Quartz cement volumes in Miller and Kingfisher aquifers can be predicted using the equations of Lander and Walderhaug (1999). This assumes local derivation and diffusive import of quartz cement and is successful in this case. The uncemented parts of these sandstones can be used to calculate that cementation in these oil reservoirs (20% residual water) is not halted by oil charge, but was reduced to become about four times lower than in the 100% water saturated sands.

Such a model can be combined now with basin modelling to predict normal or extra porosity in undrilled structures. This approach is important also in predicting the quality of aquifers beneath oilfields. Support for oil production by return flow of basin water from the aquifer is often over-estimated greatly by engineers who base their calculations on high porosity core from the oil zone. Similar effects can be anticipated in the current generation of deepwater sandstone exploration worldwide.

5. Distinguishing hydrogeology: ion microprobe analysis

Reconstructing the isotopic signature of porewater present during cement growth can test the concept of gradual and slow growth of quartz cement. This has been achieved previously by $\delta^{18}O$ measurements on physically separated quartz overgrowths. This gives a measure representing the average of the entire overgrowth population in the sandstone. It is possible to achieve greater resolution by targeting ion microbeam analysis to different in situ sectors or zones of quartz overgrowths.

In the South Brae field, quartz cement shows two sequential growth zones on SEM-CL. Ion probe $\delta^{18}O$ (Macaulay et al., 2000) shows that the inner zone (+ 24.7‰) has more + ve (positive) $\delta^{18}O$ than the outer zone (+ 21.4‰). This is compatible with the progressive slow evolution of an isotopic system in a limited volume of porewater, commencing with a meteoric influence.

Ion microprobe analyses have been made in other sandstones. In the Norwegian Garn Fmn, Williams et al. (1997) found that the inner growth zones had higher (more + ve) $\delta^{18}O$ and younger zones had less + ve $\delta^{18}O$. This was interpreted as resulting from a cool shallow burial meteoric flush followed by a more restricted or closed water system during deeper burial. This is exactly as predicted by Haszeldine et al. (1992) for the depositionally similar Brent Group sands.

In the St Peter Sst of the cratonic Michigan basin, Graham et al. (1996) made ion microprobe analyses of unzoned quartz cements sampled from the deep basin and zoned cements from a high sub-surface near the basin edge (Wisconsin Arch). The deep basin cements showed $\delta^{18}O$ less + ve and less variable than those near the basin edge implying isotopically evolved warmer fluids in the deep basin. Arch cements show isotopic evidence of upwelling warm fluid mixing, associated with nearby MVT ores.

In the southern North Sea, Sullivan et al. (1997) discovered from conventional analyses that $\delta^{18}O$ in the Leman field Permian Sst appeared uniform within quartz cements. This has been confirmed by ion microprobe now. The simplest explanation for this is that porefluids have been uniform throughout quartz growth implying convective circulation within the 200 m thick sandstone.

Thus, ion probe data on quartz cements can distinguish different palaeo-hydrogeological settings ranging from shallow meteoric to deep basinal and can distinguish meteoric from convective and from compactional expulsion even within one small sample.

6. Moving fluid: porosity creation

The Central Graben of the North Sea is rapidly subsiding with very high overpressures. Mapping the distribution of overpressure in the Upper Jurassic Fulmar Sst shows that discrete cells exist bounded by faults or depositional pinchouts (Darby et al., 1996). Unexpectedly, the intra-basin highs have significant overpressure, even though no aquiclude seal is present. It appears that fluids within the 10–50 km graben are in pressure communication over geological timescales. The overpressure regime is in dynamic equilibrium with pressure generation at depth and shallow depth vertical leakoff.

A cross-section WSW–ENE was taken by Fleming et al. (1998) across this Graben. Measured modern temperatures were taken from boreholes, corrected for drilling effects and a temperature section was established. This shows that short wavelength temperature anomalies of + 10– + 30°C occur at 2–4 km depths. These anomalies are positioned above structural features. Modelling shows that these thermal perturbations require vertical fluid flows at 100–1000 mm/yr to bring warm fluids upwards without diffusing all the heat.

Within the Fulmar Sst, overpressure leakoff occurs at regional structural highs. Sandstones sampled from these locations have lost feldspar compared to shallower sands and so become more quartzose. The porosity of these sands may be abnormally high, up to 30% at 4.7 km. Wilkinson et al. (1997) proposed that feldspar dissolution is driven by moving slowly porefluid focused towards the regional structures. This forms secondary porosity in the deep basin, which is kept open by the high overpressures. Geochemical and petrographic analyses show that aluminium must be exported from the sands, even though the volume of porefluid is low and aluminium is sometimes considered to be an ‘immobile’ element.

7. Diffusion sands-to-muds and back

Well-studied sandstones from several basins, including the USA Gulf, show trends of feldspar depletion with increased depth, which are similar to the Fulmar Sst. Comparison of geochemical data sets from shales and enclosed sandstones from the USA Gulf shows Al and K loss from sands that are balanced by increases in the enclosing muds. The muds lose C and CO_3, which may contribute to deep carbonate cements (see below). Sandstone cementation in deep basins cannot be considered to be locally isochemical—the scale of the geochemical system includes the muds at least 1–100 m away.

The interaction of muds and sands may be possible to demonstrate using natural isotopic tracers. During maturation of kerogens, organic acids are formed. There is a large range of such acids, which have a large range of −ve $\delta^{13}C$ (S. Franks, unpublished). Carbonate cements in deep-water sandstones are dominated by $\delta^{13}C$-12 (Macaulay et al., 1998), indicating a transfer of ^{12}C from muds to sands. Deepwater sands of the Magnus field are a good location to study such transfer as they represents a discrete and locally-bounded hydrocarbon system enclosed by the Kimmeridge Clay (KCF) source rock (Ballentine et al., 1996). Here, the late low $\delta^{13}C$ carbonates are more abundant close to mudrocks. The −ve $\delta^{13}C$ signature only occurs where the sand is overlain by the KCF and a more + ve $\delta^{13}C$ signature occurs where the sand is overlain by marls—indicating local C supply.

Kaolin and illite clays formed during burial are extraordinarily depleted often in δD. This effect occurs also in the Magnus field and has a systematic relationship with $\delta^{18}O$ of palaeo-water (Fallick et al., 1993). Porewater volumes within the Magnus system are well constrained so that ‘diffusion’ from enclosing KCF muds to the centre of sandbodies >100 m distant is the probable transport mechanism. Transport could be assisted by lateral dispersion within porewater being displaced during oil charge.

Timing of illite growth within the Magnus field can be dated by K–Ar. These dates (70–40 Ma) can be matched to calibrate predictions of the duration of oil charge made by BasinMod™ 2D modelling (Cavanagh in prep). On a regional 50 km compilation, illite growth on fault terraces at the edge of the Viking Graben shows a progressive younging away from the Graben, suggesting strongly that illite in this case was controlled by the local oil charge within a fill-spill sequence and not by the hydrothermal episodes.

8. Conclusions

Sedimentary basins are dynamic geochemical and fluid systems. Distinct fluid settings can be distinguished including: meteoric, lateral compaction, convection and vertical leakoff. The volumes of fluid involved may become progressively smaller with depth. Solute transport may be predominantly diffusive, though any advective motion could greatly increase transport rates by lateral dispersion. Oil charge slows cementation greatly and thereby preserving porosity. Secondary porosity can form from feldspar at depth and progressively changes arkoses to quartzites. Al and K are lost from sands to muds, whilst low δ^{13}C and low δD are imported from muds. Integrated micro-analytical studies can reduce greatly the ambiguity of general models, help understand porosity–permeability controls and reconstruct past hydrogeology.

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