

## Fracture cementation mechanisms in the North Sea

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Most quantitative models of transport and diagenetic reactions in sedimentary basins concentrate on processes within the porous network, where fluid flow typically is driven by sediment compaction. Such flow seldomly takes place with fluid velocities higher than  $1 \text{ mm y}^{-1}$ , and representative velocities are only a fraction of that. In open fractures (joints and faults), however, moving fluids may reach velocities of  $1\text{--}100 \text{ m y}^{-1}$  (Pedersen *et al.*, 1997). This range refers to fractures contained within the sediments; fractures that extend to the surface may allow much higher velocities. The relatively high velocities as well as small specific surface of open fractures enhance the importance of advection and kinetics relative to in the surrounding porous medium, and conclusions on diagenetic processes drawn from studies of the porous medium may not be valid for fractures. Fractures are abundant in sedimentary basins, and it is important to investigate the diagenetic mechanisms operating in them.

The main purpose of the present communication is to report on fracture cements in the sediments of the North Sea. From these observations as well as theoretical analysis, we try to constrain the transport mechanism(s) responsible for cementation. Our database containing records of cemented fractures in the North Sea is restricted to areas away from major fault zones, and the inferences drawn may not be representative for fractures intimately associated with such features, nor within the fault and fault zones themselves.

### Observations

The cemented fractures occur in various lithologies in the North Sea, including sandstones, mudstones, limestones and volcanics. They are typically subvertical and their widths are usually a few mm, rarely exceeding 1 cm. The observed types of minerals include carbonates, kaolinite, baryte and pyrite. Quartz is only found in association with strongly altered mafic intrusions. Calcite, dolomite, ankerite and siderite are all observed, calcite being

the most abundant mineral. The wall rock cement is normally also carbonate, but chemically distinct from the vein mineral (e.g. siderite versus dolomite or calcite). Carbon isotope measurements demonstrate that the carbon source for fracture mineralisation was different from that of the local wall rock cement. Multiple generations of carbonate cementation in the fractures are common, and precipitation of carbonate prior to a quite different mineral phase like kaolinite is occasionally observed.

### Theory

The abundance of carbonates and virtual lack of quartz as a fracture mineral is puzzling when solubility is considered. The solubility of quartz will typically decrease with reduction in temperature and pressure, and saturated fluids flowing upwards through an open fracture should precipitate quartz. On the other, carbonates have retrograde solubility, and fluids experiencing a decrease in pressure and temperature as they flow upwards should dissolve rather than precipitate carbonates. That quartz is not found can be explained as a kinetic effect. At the relatively low temperatures the cores described in our database have been subjected to, normally less than  $150^\circ\text{C}$ , the kinetics is too slow to allow precipitation within fractures (Pedersen *et al.*, 1997). To explain the abundance of fracture carbonate cement is more difficult.

To explore the various potential mechanisms for precipitation of carbonates in fractures, it is useful to divide them into two groups: local transport of solutes from the wall rock, and import of solutes from fluids flowing upwards in the fracture. Transport of solutes from the wall rock into the fracture may occur by either advection of the pore fluid or by diffusion caused by concentration gradients. That advection is an unlikely cementation mechanism can be readily established by simple mass balance calculations. With a specific surface of calcite equal to  $3.7 \times 10^{-5} \text{ m}^3 \text{ mol}^{-1}$  and a solubility contrast of  $0.05 \text{ mole m}^{-3}$  (appropriate for a pressure

difference of 1 MPa, a temperature of 100°C, total pressure equal to 40 MPa and  $P_{\text{CO}_2} = 0.5$  MPa) between matrix and fracture, a 1 mm thick cemented fracture would require  $5 \times 10^2 \text{ m}^3 \text{ fluid m}^{-2}$  fracture wall surface. Such high fluid volumes cannot realistically be derived from the wall rock. For a porosity of 10%, the width over which fluid had to be drained into the fracture would be approximately 5 km, even if all the water were considered to be available. A pressure difference of 1 MPa is probably close to maximum (Fisher and Brantley, 1992), and in most cases the solubility difference will be lower than  $0.05 \text{ mole m}^{-3}$ . The required volumes of fluid will then be correspondingly larger.

The solubility contrast between matrix and fracture defines a concentration gradient that may drive solutes into the fracture. Assuming constant solubility contrast and tentatively neglecting the low permeability of the growing cement coating (cf. Fisher and Brantley, 1992), we find that only about  $10^3 \text{ y}$  are required to produce 1 mm of calcite for a solubility contrast of  $0.05 \text{ mole m}^{-3}$ . This mechanism would, however, produce a depleted zone around the fracture, of which there is no evidence in our data. Furthermore, the growing layer of carbonate cement represents a low porosity zone with a very low bulk diffusion coefficient (Farver and Yund, 1991), here estimated to  $10^{-13} \text{ m}^2 \text{ s}^{-1}$ . Taking this barrier effect into consideration, the time required growing 1 mm of cement increases to  $10^5 \text{ y}$  for a pressure difference of 1 MPa, and to  $10^7 \text{ y}$  for a pressure difference 1% of that. Although there are considerable uncertainties associated with these calculations, we suggest that these time spans may be in the lower range. The main reason being that the calculations are based on the assumption that the pressure difference, and hence solubility contrast, remains constant with time. In reality, there will probably be a reduction in pressure after the fracture has been established. This effect will further increase the time needed for producing the cement.

Supersaturated fluids flowing upward in the fracture at relatively high speeds represent another potential cementation agent. Using recent experimental data on calcite precipitation in fractures (Lee *et al.*, 1995), we find that an only slightly supersaturated fluid ( $+0.05 \text{ mole m}^{-3}$  or 1% supersaturation at the fracture inlet) could produce 1 mm of cement in about  $10^5$  years if the fluid flows with a velocity of  $100 \text{ m y}^{-1}$ . Much higher degrees of supersaturation are difficult to reconcile with the observation that the thickness of the cemented fractures varies little (typically less than 20%) on the 10-cm (core diameter) scale of our samples. For

50% supersaturation, only  $10^2 \text{ y}$  is required to produce 1 mm of cement. However, in order for the thickness of the cement not to vary more than observed along the length of the fracture, the fluid has to move with a velocity of  $10^3 \text{ m y}^{-1}$ . Such velocities are, however, difficult to sustain for the type of fractures we are considering here (Pedersen *et al.*, 1997). Furthermore, a high degree of supersaturation and high fluid velocities would yield high precipitation rates. Rapid growth of cement is considered to result in a fibrous fabric (Gonzales *et al.*, 1992), which is incompatible with the equant grains that dominate our samples.

## Conclusions

The following conclusions can be drawn from this work on cemented fractures in the North Sea:

1. Carbonates are common as fracture cement, whereas quartz is virtually absent.
2. Considerable differences in mineralogy and carbon isotope values between fracture cement and matrix are often found. This indicates that cementation by imported upwards flowing fluids is common.
3. Mass balance calculations demonstrate that advection of solutes from the wall rock is an unlikely cementation mechanism.
4. Diffusion from the wall rock can produce mm-thick fractures in  $10^5 \text{ y}$  for a solubility difference of  $0.05 \text{ mole m}^{-3}$ . However, we find no evidence for a depleted zone around the fracture. If the cement was derived by dissolution of carbonates in the local wall rock, there should have been such a zone.
5. Slightly supersaturated fluids flowing upwards through the fracture at velocities of  $10^2 \text{ m y}^{-1}$  can produce the observed fracture cements. Uncertainties in the actual degree of supersaturation as well as in the kinetics of calcite precipitation and solution chemistry inhibits, however, our possibility to define the fluid velocities with precision.
6. High degrees of supersaturation would tend to clog the fracture at its inlet, while what are observed are fractures with fairly constant thicknesses at the 10 cm scale.
7. The time required for generation of the mm-thick fractures is crudely estimated to be  $10^5 \text{ y}$  or more. They may thus constitute an important factor to be considered in studies of fluid flow in sedimentary basins over geological time spans.

## References

- Farver, J.D. and Yund, Y.A. (1991) *Geochim. Cosmochim. Acta.* **55**, 1597–1607.