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ABSTRACTS

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Quartz Cementation of a Faulted Sandstone at Shallow Burial: Petrographic and Poroperm Data: UK North Sea

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Quartz cement is a major culprit of porosity and permeability loss in deeply buried sandstone hydrocarbon reservoirs. A major debate is whether quartz cement is entirely internally derived or if fluid flow and mass transfer can import silica for quartz cementation. North Sea sandstones typically display the onset of significant quartz cementation at a burial depth of 2.7km, equivalent to 80ºC. Successful computer models of quartz cementation in such reservoirs1 assume that silica for cementation is supplied internally, from pressure solution between detrital quartz grains, and that cementation is controlled by rate of precipitation. Intra-sand distribution of cement is controlled by facies related characteristics such as clay coatings and grain size variation.

A case of exotic, structurally related, quartz cementation emplaced at shallow burial depth is documented here; giving insight into fault-fluid interaction through unravelling of the diagenetic products of the process.

Two normal cataclasite faults are well exposed in three dimensions within the aeolian (U.Permian) Hopeman Sandstone, exposed onshore within the Inner Moray Firth basin, UK North Sea. Fault one is sub-seismic scale with a throw 8-40m, with Hopeman Sandstone in both the footwall and hanging wall. Individual, rare, deformation bands are visible for up to 10m either side of the main slip face, which is composed of a 50cm thick fault gouge and cluster of anastamosing deformation bands. Fault 2 is a seismic scale fault with a throw of c.100m, a c.30m damage zone comprising isolated single deformation bands which give way to anastamosing clusters of bands nearer the fault plane. Clean Triassic fluvial sands are downthrown in the hanging wall against the U.Permian Hopeman Sandstone in the footwall to the north.

Integration of seismic data, onshore maps and field data shows that the faults are contained within an uplifted horst block on the margin of the 50km wide, 5km deep, half-graben basin. This formed a structural focus for regional fluid expulsion from the basin. Maximum burial depth of the Hopeman Sandstone within this horst block is less than 1.5km based upon petrography, structure and basin history. The two exposed faults underwent late Jurassic extension, coeval with the major phase of basin development, prior to Palaeocene regional uplift which resulted in selective fault re-activation basinwide. A total of seventy petrographic samples were taken from both fault outcrops in traverses perpendicular to the fault plane, through the footwall, across the fault plane and into the hanging wall. Quantitative petrographic analysis of the sandstone using SEM-CL reveals an asymmetric pattern of quartz cementation across both fault planes.

In sub-seismic Fault 1, moving through the footwall toward the fault plane, quartz cement volume increases from 5.6% at 31m to a maximum of 26.5% 13m from the plane. From 10m distant to the fault plane authigenic quartz volume decreases from 17.2% to 4.2% in a linear pattern. Small remnant crystals of carbonate within the footwall, and occasionally elsewhere in the Hopeman Sandstone, indicate a nodular and patchy carbonate cement was emplaced pre-authigenic quartz, specifically in the zone between the fault plane and 10m into the footwall. This localised carbonate cement reduced the space available for authigenic quartz precipitation in this zone, resulting in variable amounts of quartz cement. The hanging wall contains 5% authigenic quartz at 2m from the fault plane, and quartz cement volume remains a mean 3% up to 30m from the footwall. Background samples from exposures distal to structural features display an average quartz cement of 4%. Under CL imaging 2 phases of quartz cement are visible. Phase 1 is fault-related, and occurs in the well cemented footwall sands where quartz cement displays a bright luminescent mottled signature. Phase 2, a darker luminescence, forms hanging wall and background sandstone overgrowths, as well as some late stage cement within footwall overgrowths. Cementation cross-cuts facies in both faulted outcrops and is not preferentially developed, or preferentially absent, from any particular facies.

Porosity displays an inverse relationship to quartz cement across the fault plane. Footwall porosity decreases from 24% at 31m from the fault plane through to 10% at 10m. In the footwall zone 10m-0m porosity varies inversely with the volume of quartz cement in each sample. Hanging wall porosity is 23% at 2m from the fault plane and rises to a relatively consistent value of 25% from 2-30m, and in background outcrop samples. Permeability follows a similar asymmetric trend as porosity. Footwall, field-measured, permeability decreases approaching the fault plane from 10-100mD to 1-10mD, as cement volume increases. Permeability of the fault plane is <1mD measured perpendicular to the main slip face. In poorly cemented hanging wall, and background sandstones, permeability is 100-700mD. Fault-related quartz cementation reduces permeability by 2 orders of magnitude in footwall fault-adjacent sandstone.

At the seismic scale Fault 2, footwall quartz cement volume is consistently high and increases moderately from 26% at 13m from the fault plane to 31% at 1m from the fault plane. Samples from Fault 2 are all within the fault ‘damage’ zone, but avoid deformation band features. The fluvial sands in the hanging wall contain 5% quartz cement and nodular carbonate cement. Porosity and permeability follow an inverse trend to quartz cement, footwall sands display a decrease from 11% at 13m to 1% at 1m. Hanging wall sands contain an average 16% porosity. Footwall permeability varies between <1mD to <10mD with a broad increase in permeability with increasing distance from the main slip face.

At sub-seismic fault 1, footwall intergranular volume (pore space+ cement) increases from 27% at 32m to 33% at 13m. Extensive cement in footwall adjacent sands has prevented mechanical compaction post-cementation, and preserved intergranular volume. Less well cemented sands at greater distance from the fault recorded further compaction post-cementation, indicating that the fault-associated quartz cement was emplaced pre-maximum burial. At the seismic scale fault, footwall intergranular volume is consistently high, but increases slightly from a minimum of 28% at 13m to 32% at 1m. The average absolute value of intergranular volume, in poorly cemented background sandstones distant from structural features, is 28%, indicating that maximum burial was <1.5km and that burial conditions of pressure solution were not reached. The average intergranular volume of the whole well cemented footwall sample set, at both fault 1 and fault 2, is 31% which equates to the predicted state of compaction of an uncemented quartzose sand at a burial depth2 of <1km. This indicates quartz cement was emplaced at a burial depth of <1km, freezing subsequent compaction processes.

Regional extrapolation of thickness of the overlying strata at the onset of the Late Jurassic equates to the c.1km depth of burial at the time of cementation, suggesting that cementation is coevally as well as spatially related to the Late Jurassic extensional fault planes.

Fluid inclusions along quartz detrital grain-overgrowth boundaries are mostly single phase, aqueous, indicating low temperature cement precipitation with Th <60ºC. Some inclusions are large and very irregular, with extreme liquid:vapour ratios. These are interpreted to form in the partly-saturated sandstone arid-region aquifer. Frequent, similarly oriented, pseudo-secondary trails of 2-phase aqueous inclusions are present in multiple detrital grains, with individual trails truncating at the detrital grain-overgrowth boundary, indicating that they pre-date quartz overgrowth. The similar orientation of the trails, in randomly oriented grains, are interpreted as healed micro-fractures generated during fault movement. Measured homogenisation temperatures are >130-160ºC, recording the presence of hot fluids in the sandstone at the time of faulting.

Ion probe in-situ analysis of quartz overgrowth Oxygen isotope values reveals, for footwall cements in the sub-seismic fault, a mean value of 18O 19.6‰ +/-0.2‰ (SMOW) with a range of 18O 15.1‰ +/-1‰ to 25.8‰ +/-1‰. In the footwall of the seismic scale fault, average quartz cement 18O is 19.4‰ +/- 0.2‰, with a range of 18O 16.2‰ to 24.3‰. 18O values show a moderate increase with increasing distance from the fault plane in the sub-seismic fault. In the seismic scale fault all samples are within the fault zone and 18O shows no significant trend with distance. Hanging wall and background samples of Hopeman Sandstone contain mean 18O 21.1‰ with a much reduced range of 18O 20.1‰ to 22.0‰

Systematic analysis of isotope values in profiles through individual quartz overgrowths, from the grain –cement boundary to overgrowth edge, from both fault plane footwalls, reveals 18O values are most heterogeneous in early quartz cement adjacent to the detrital grain. This zone also contains the lowest d18O values, leading to the large range in average footwall isotope values observed. Isotope value range is relatively restricted to higher 18O values in later stage footwall cement where values approach those measured in hanging wall and background sands.

High homogenisation temperatures in pseudo-secondary fluid inclusion trails indicate hot ascending fluids entered the footwall of the permeable Hopeman Sandstone during Late Jurassic faulting. This formed a "blind" hot spring, discharging into subsurface permeable sands. The cooler homogenisation temperatures of quartz overgrowths (<60ºC) indicate quartz cement precipitated during cooling of the exotic fluids toward background rock temperatures which were c.20ºC at 1km burial depth. Combining fluid inclusion Th and Oxygen isotope values indicates that early footwall quartz overgrowths precipitated from hot basinal fluids which mixed with slightly modified meteoric fluids, incorporated on burial of the Hopeman Sandstone, resulting in a high range of Oxygen isotope values. As quartz cement growth continued cooler fluids began to dominate, increasing the value of 18O and reducing the spread in values. Hanging wall cements represent the earliest stages of internal, burial, quartz cementation sourced from feldspar dissolution and minor pressure solution in the presence of meteoric fluids. Quartz cement asymmetry across the faults is a product of fault-fluid interaction, and not facies variation, as grain-fall and toe-set facies are seen in both the hanging and foot walls. Early development of low permeability fault gouge on the hanging wall side of the fault planes favoured fluid entry into the footwall.

References

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