Naturally propped fractures caused by quartz cementation preserve oil reservoirs in basement rocks

Baba, M., Parnell, J., Bowden, S.A.

School of Geosciences, University of Aberdeen, Aberdeen AB24 3UE, UK,

Abstract

Much silica precipitation in oil reservoirs occurred in the presence of hydrocarbons, evidenced by the entrapment of oil fluid inclusions in quartz. Also, silica in sedimentary basins is commonly precipitated at oil-window temperatures. This spatial and temporal relationship between oil and quartz precipitation aids the entry of oil into fractured reservoirs, including fractured basement. Where quartz is precipitated as fracture linings, the fractures are propped open by bridging quartz crystals, creating high fracture porosity and permeability. Evidence from fossil fractured reservoirs shows a large proportion of oil residue is in such propped open fractures.

Introduction

Fractured reservoirs make an important contribution to hydrocarbon resources (Nelson 2001, Lonergan et al. 2007). The porosity and permeability of fractured reservoirs are strongly dependent upon fracture aperture (Olson et al. 2007, Caulk et al. 2016, Bisdom et al. 2016). A desirable combination of high porosity and high permeability can be achieved where a wide aperture is propped open by asperities, typically where quartz-lined fractures are bridged by euhedral quartz crystals (Laubach et al. 2004, Olson et al. 2007). Existing models for quartz bridging of fractures assume that quartz precipitation occurs from simple, silica-saturated fluids (Lander & Laubach 2015). The precipitation rate controls whether quartz is euhedral or not, forming bridges or fracture linings (Lander & Laubach 2015). An incremental crack-seal precipitation can last up to tens of millions of years (Becker et al. 2010, Fall et al. 2012).

In hydrocarbon-bearing systems, quartz precipitation can be modified in cases where it occurs from mixed aqueous-oil fluids. There is abundant evidence for deposition from mixed fluids in the entrapment of oil fluid inclusions in quartz overgrowths in sandstones, in authigenic quartz crystals in limestones, and in low-temperature quartz veins (e.g. Levine et al. 1991, Parnell et al. 1996, O'Reilly & Parnell 1999, Suchy et al. 2010). Euhedral quartz crystals contain oil inclusions so consistently, sometimes visible to the naked eye, that a genetic relationship between the occurrence of oil and quartz precipitation is probable. The precise mechanism is unclear, but evidence from nanotechnology shows that in oil-water emulsions silica precipitation can be nucleated at the fluid interface (Schacht et al. 1996, Finnie et al. 2007, Koźlecki et al. 2016) and fluctuations between oil-wet and water-wet conditions influence what inclusions are trapped. This is important to fracture systems where oil inclusions show that bridging quartz crystals were precipitated in the presence of hydrocarbons, so that the hydrocarbons have aided the preservation of their own host porosity.

This study reports three examples of exhumed fossil fractured reservoirs in Precambrian basement rocks, where oil inclusions show that oil was present during precipitation of fracture-lining quartz. The objectives are:

(i) To assess any evidence that bridged quartz veins aided oil ingress, using the distribution of solid oil residues (bitumen).

(ii) To assess if the quartz grew by an incremental crack-seal process, or by growth into open space.

(iii) To constrain the temperature of oil ingress using the oil inclusions entrapped in fracture-lining quartz.

Methodology

Petrographic and fluid inclusion studies were undertaken using three case studies in the U.K., in which fractured Precambrian basement rocks were charged by oil from younger sedimentary basins:

(i) Precambrian (Longmyndian) metasediments at Bayston Hill, Shropshire, England, where fractures contain oil residues derived from Carboniferous coal-bearing sediments (Parnell et al. 2017b).

(ii) Precambrian metasediments at Old Radnor, Powys, Wales, where fractures contain oil residues attributed to a Lower Palaeozoic source (Parnell et al. 1991).

(iii) Precambrian (Moinian) gneisses and overlying Devonian conglomerates in Ross-shire, Scotland, where fractures contain oil residues derived from shales within the Devonian succession (Parnell et al. 2017a).

Scanning electron microscopy (SEM) was conducted in the Aberdeen Centre for Electron Microscopy, Analysis and Characterisation (ACEMAC) facility at the University of Aberdeen using a Carl Zeiss GeminiSEM 300 VP Field Emission instrument equipped with Deben Centaurus CL detector, an Oxford Instruments NanoAnalysis Xmax80 Energy Dispersive Spectroscopy (EDS) detector, and AZtec software suite. The operating voltage was 15kV for EDS analysis, 8 kV for backscattered analysis.

Fluid inclusion studies were performed on doubly polished wafers using a Linkam THMS-600 heating–freezing stage mounted on a Nikon Labophot transmission light microscope. The instrument equipped with a range of objective lenses including a 100× lens, was calibrated against synthetic H_2O (374.1 and 0.0 °C) and CO_2 (− 56.6 °C) standards (Synthetic Fluid Inclusion Reference Set, Bubbles Inc., USA). The petrography of fluid inclusion assemblages was first examined at low magnifications using a NIKON Eclipse E600 microscope equipped with both transmitted white and incident ultraviolet light (UV) sources. Ultraviolet light, with an excitation wavelength of 365 nm, was provided by a high pressure mercury lamp with a 420 nm barrier epi-fluorescence filter.

Results

Petrography

In each of the case studies, the basement rock is cross-cut by fractures up to 2 mm aperture. Fractures 1-2 mm width are lined with quartz typically 100-300 microns thickness, with bridging quartz for 25-50 % of the fracture length. The remaining fracture porosity is filled with solid bitumen. Where the fracture aperture thins to less than 1 mm, it is usually sealed completely by quartz. CL-SEM studies of the quartz linings show euhedral crystal faces into the fractures (Fig. 1). The quartz exhibits relatively simple growth zoning which can be correlated between adjacent crystals, and which indicates that the crystals grew progressively bigger until the available space was filled (Fig. 2). The quartz does not exhibit discontinuities that might indicate multiple episodes of fracture growth.There is no evidence of crack-seal texture, including in the quartz bridging across the entire width of the fractures.

Fluid Inclusions

Quartz crystals in the fractures contain both aqueous and oil fluid inclusions, which appear to be coeval. The quartz in samples from Old Radnor contains primary oil inclusions large enough for microthermometry (Fig. 3). The oil inclusions are coloured yellow, fluoresce under ultra-violet light, and are up to 50 microns size, in contrast to the accompanying aqueous inclusions which are micron-scale (Fig. 4). Homogenization temperatures are in the range 72 to 125 °C (mean 109.8 °C, n = 10). Aqueous inclusions in quartz from fracture-fills in Ross-shire yield temperatures in the range 99 to 117 °C (Parnell 1996), and calcite accompanying quartz at Bayston Hill yield a range from 85 to 125 °C (Parnell et al. 2017b). Measurements are from a single fluid inclusion assemblage in each case, from multiple quartz crystals.

Discussion

Several characteristics of the quartz show that it grew in a manner distinct from the crack-seal process observed previously in sandstones. Firstly, the abundant euhedra (Fig. 1) indicate a simple growth process. Secondly, the textures seen in SEM-CL show no evidence for crack-seal growth.

Instead, the euhedral faces indicate growth into open space, so the fractures were not repeatedly forced open. The evidence for simple growth in a single fracture-filling episode rather than crack-seal suggests that quartz precipitation was less protracted than the tens of millions of years inferred for crack-seal elsewhere (Becker et al. 2010). We cannot completely exclude protracted filling of an open fracture, but emphasize that the fractures are propped open by the quartz and would have closed without it.

The occurrence of primary oil inclusions shows that the quartz grew from a fluid that was already oil-bearing in advance of the oil that filled the remaining fracture porosity. Oil inclusions in quartz are a common feature of euhedral quartz in sedimentary basins. In these case studies, fluids derived from sedimentary basins have penetrated to adjacent basement rocks. The temperatures indicated by the basement-hosted oil fluid inclusion data, in the range 72 to 125 °C, are typical for oil inclusions trapped in quartz overgrowths in sedimentary basins (Walderhaug 1994). These temperatures are broadly coincident with the temperature window of oil generation, commonly cited at 60 to 120 ˚C (Hunt 1996). The co-occurrence of oil and water inclusions implies that the pressure correction to the homogenization temperatures is minimal (Parnell et al. 1996). The fracture linings and overgrowths represent a continuum of quartz precipitation in the available space, leaving a stable framework for oil to fill the remaining porosity. The requirement for quartz to bridge open the fractures implies that this is a feature characteristic of several kilometres depth, where the temperatures are high enough for quartz precipitation.

The availability of porosity for oil entrainment indicates that quartz cementation did not continue to completely fill the fractures. One possibility is that the rocks were uplifted and cooled below the temperatures of quartz precipitation before complete cementation. However, the generation of oil implies that cooling did not occur until post-oil emplacement. Alternatively, the propping quartz cement formed at low oil saturations, adequate to enable trapping of oil inclusions, but not enough to inhibit quartz precipitation, then oil saturations rose to the point where cementation was inhibited, and fractures were preserved. In each case, oil generation increased to a point where veins of bitumen formed (Parnell et al. 1991, 2017a,b), evidencing that an increase in oil saturation was indeed involved.

Mapping of carbon shows that almost all of the oil residue is within the fracture system (Fig. 5). This shows the importance of the quartz bridges in creating porosity to allow ingress of oil into the basement. In the Precambrian basement rocks studied, fractures represent the only significant porosity, evidenced by very low permeability values and water flow almost entirely through fractures (Jones et al. 2000, MacDonald et al. 2005). Without the precipitation of the quartz bridges, there would be little or no porosity and oil in the rocks.

Conclusions

The case studies show how oil can enter fractured reservoirs that were mineralized by hydrocarbon-bearing fluids. In particular:

(i) Fracture linings, including bridging quartz crystals, were precipitated by hydrocarbon-bearing fluids following a single fracturing episode, rather than long-term repeated crack-seal.

(ii) The precipitation of bridging quartz cement meant continuing oil ingress was able to take advantage of stabilized fracture porosity.

(iii) The quartz was precipitated over the temperature range 72 to 125 °C, characteristic of the temperatures of oil generation, and similar to that of quartz cementation in sedimentary basins.

These observations combine to show that oil in the mineralizing fluid influenced the preservation of open fractures. When there is increasing interest in the detailed petrographic history of commercial fracture reservoirs (Gutmanis 2009, Trice 2014), this study shows how oil can contribute to its own porosity.

Acknowledgements

MB is in receipt of a postgraduate studentship from PTDF (Nigeria). Skilled technical support was provided by M. Baron and J. Still. Two reviewers made valuable criticisms that improved the paper.

References

Becker, S.P., Eichhubl, P., Laubach, S.E., Reed, R.M., Lander, R.H. & Bodnar, R.J. 2010. A 48 m.y. history of fracture opening, temperature, and fluid pressure: cretaceous Travis Peak Formation, East Texas basin. Geological Society of America Bulletin, 122, 1081-1093.

Bisdom, K., Bertotti, G. & Nick, H.M. 2016. The impact of different aperture distribution models and critical stress criteria on equivalent permeability in fractured rocks. Journal of Geophysical Research: Solid Earth, 121, 4045-4063.

Caulk, R.A., Ghazanfari, E., Perdrial, J.N. & Perdrial, N. 2016. Experimental investigation of fracture aperture and permeability change within Enhanced Geothermal Systems. Geothermics, 62, 12-21.

Fall, A., Eichhubl,P., Cumella, S.P., Bodnar, R.J., Laubach, S.E. & Becker, S.P. 2012. Testing the basin-centered gas accumulation model using fluid inclusion observations: Southern Piceance Basin, Colorado. AAPG Bulletin, 96, 2297-2318.

Finnie, K.S., Bartlett, J.R., Barbé, C.J.A. & Kong, L.G. 2007. Formation of silica nanoparticles in microemulsions. Langmuir, 23, 3017-3024.

Gutmanis, J.C. 2009. Basement reservoirs – A review of their geological and production characteristics. International Petroleum Technology Conference paper IPTC 13156.

Hunt, J.M. 1996. Petroleum Geochemistry and Geology. W.H. Freeman & Co., San Francisco.

Jones, H.K., Morris, B.L., Cheney, C.S., Brewerton, L.J., Merrin, P.D., Lewis, M.A., MacDonald, A.M., Coleby, L.M., Talbot, J.C., McKenzie, A.A., Bird, M.J., Cunningham, J. & Robinson, V.K. 2000. The Physical Properties of Minor Aquifers in England and Wales. British Geological Survey Technical Report, WD/00/4.

Lander, R.H. & Laubach, S.E. 2015. Insights into rates of fracture growth and sealing from a model for quartz cementation in fractured sandstones. Geological Society of America Bulletin, 127, 516-538.

Laubach, S.E., Reed, R.M., Olson, J.E., Lander, R.H. & Bonnell, L.M. 2004. Coevolution of crack-seal texture and fracture porosity in sedimentary rocks: cathodoluminescence observations of regional fractures. Journal of Structural Geology, 26, 967-982.

Levine, J.R., Samson, I.M. & Hesse, R. 1991. Occurrence of fracture-hosted impsonite and petroleum fluid inclusions, Quebec City region, Canada. AAPG Bulletin, 75, 139-155.

Liu, Q., Yuan, S., Yan, H. & Zhao, X. 2012. Mechanism of oil detachment from a silica surface in aqueous surfactant solutions: Molecular dynamics simulations. Journal of Physical Chemistry B, 116, 2867-2875.

Lonergan, L., Jolley, R.J.H., Rawnsley, K. & Sanderson, D.J. 2007. (eds) Fractured Reservoirs. Geological Society, London, Special Publications, 270.

Koźlecki, T., Polowczyk, I., Bastrzyk, A. & Sawiński, W. 2016. Improved synthesis of nanosized silica in water-in-oil microemulsions. Journal of Nanoparticles, doi:10.1155/2016/8203260.

MacDonald, A.M., Robins, N.S., Ball, D.F., Ó Dochartaigh, B.É. 2005. An overview of groundwater in Scotland. Scottish Journal of Geology, 41, 3-11.

Nelson, R.A. 2001. Geological Analysis of Naturally Fractured Reservoirs (Second Edition). Elsevier, Amsterdam.

Olson, J.E., Laubach, S.E. & Lander, R.H. 2007. Combining diagenesis and mechanics to quantify fracture aperture distributions and fracture pattern permeability. In: Lonergan, L., Jolly, R.J.H., Rawnsley, K. & Sanderson, D.J. (eds) Fractured Reservoirs. Geological Society, London, Special Publications, 270, 101-116.

O'Reilly, C. & Parnell, J. 1999. Fluid flow and thermal histories for Cambrian-Ordovician platform deposits, New York: Evidence from fluid inclusion studies. Geological Society of America Bulletin, 111, 1884-1896.

Parnell, J. 1996. Alteration of crystalline basement rocks by hydrocarbon-bearing fluids: Moinian of Ross-shire, Scotland. Lithos, 37, 281-292.

Parnell, J., Baba, M. & Bowden, S. 2017a. Emplacement and biodegradation of oil in fractured basement: the 'coal' deposit in Moinian gneiss at Castle Leod, Ross-shire. Earth and Environmental Science Transactions of the Royal Society of Edinburgh, in press.

Parnell, J., Baba, M., Bowden, S. & Muirhead, D. 2017b. Subsurface biodegradation of crude oil in a fractured basement reservoir, Shropshire, UK. Journal of the Geological Society, London, 174, 655-666.

Parnell, J., Carey, P. & Monson, B. 1996. Fluid inclusion constraints on temperatures of hydrocarbon migration from authigenic quartz in bitumen veins. Chemical Geology, 129, 217-226.

Parnell, J., Robinson, N. & Brassell, S. 1991. Discrimination of bitumen sources in Precambrian and Lower Palaeozoic rocks, Southern U.K., by gas chromatography-mass spectrometry. Chemical Geology, 90, 1- 14.

Schacht, S., Huo, Q., Voigt-Martin, I.G., Stucky, G.D. & Schüth, F. 1996. Oil-water interface templating of mesoporous macroscale structures. Science, 273, 768-771.

Suchy, V., Dobeš, P., Sykorová, I. & Matysová, P. 2010. Oil-bearing inclusions in vein quartz and calcite and bitumens in veins: testament to multiple phases of hydrocarbon migration in the Barrandian basin (Lower Palaeozoic), Czech Republic. Marine and Petroleum Geology, 27, 285-297.

Trice, R. 2014. Basement exploration, West of Shetlands: progress in opening a new play on the UKCS. In: Cannon, S.J.C. & Ellis, D. (eds) Hydrocarbon Exploration to Exploitation West of Shetlands. Geological Society, London, Special Publications, 397, 81-105.

Walderhaug, O. 1994. Temperatures of quartz cementation in Jurassic sandstones from the Norwegian continental shelf – evidence from fluid inclusions. Journal of Sedimentary research, A64, 311-323.

Figure captions

Fig. 1. Scanning electron image showing authigenic quartz crystals within bitumen (dark) from fracture through metasedimentary basement, Bayston Hill. B, bitumen; Q, quartz. Scale bar 125 microns.

Fig. 2. Fracture bridged by quartz and containing bitumen, Bayston Hill. (a) back-scattered image, (b) cathodoluminescence image. Back-scattered image shows infill of quartz (grey), calcite (bright) and bitumen (dark). Cathodoluminescence images shows quartz grew as euhedra with simple growth zones. B, bitumen; C, calcite, Q, quartz.

Fig. 3. Temperatures of fracture-bridging quartz in three case studies, from fluid inclusion data. Data ranges overlap temperature window of oil generation.

Fig. 4. Photomicrograph of quartz, Old Radnor, containing oil fluid inclusions (H, large, yellow) and aqueous inclusions (A, very small, colourless).

Fig. 5. Paired back-scattered image and carbon element maps for mineralized bitumen (oil)-bearing fracture through Proterozoic gneiss, Strathpeffer (A, B) and Proterozoic conglomerate, Bayston Hill (C, D). Carbon map shows bitumen is limited to fractures.