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Natural fracture propping and earthquake-induced oil migration in fractured basement reservoirs

Holdsworth, R.E.[1,2], McCaffrey, K.W.J.[1,2], Dempsey, E.[3], Roberts, N.M.W.[4], Hardman, K.[1], Morton, A.[5], Feely, M.[6], Hunt,J.[6], Conway, A.[7]

1 Department of Earth Sciences, Durham University, UK
2 Geospatial Research Ltd, Durham, UK
3 School of Environmental Sciences, University of Hull, UK
4 British Geological Survey, Nottingham, UK
5 HM Research and CASP,, UK.
6 NUI, Galway, Ireland.
7 CONSCO Ltd, UK

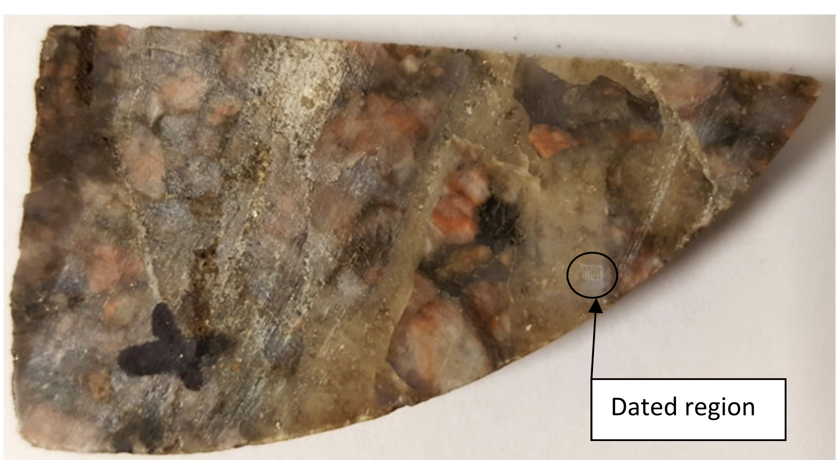
U-PB GEOCHRONOLOGY

Calcite U-Pb geochronology was conducted via Laser Ablation Inductively Coupled Mass Spectrometry (LA-ICP-MS) *in-situ* in polished blocks, at the NERC Isotope Geosciences Laboratory (Nottingham, UK) using a New Wave Research 193UC laser ablation system coupled to a Nu Instruments Attom ICP-MS, following a standard matrix-matched sample-bracketing method (see Beaudoin et al., 2018; Roberts & Walker, 2016). Laser parameters were a pre-ablation for 3 s using a 150 µm spot, and ablation for 30 s with a 100 µm spot at 10 Hz and 8 J/cm^2. Normalisation of U-Pb ratios was achieved with the reference material WC-1 (Roberts et al., 2017), and Pb-Pb ratios were normalised using NIST 614 silicate glass (Woodhead & Hergt, 2001). Duff Brown carbonate (64.04 ± 0.67 Ma; Hill et al., 2016) was analysed in the same session to provide validation, and yielded a lower intercept age of 64.2 ± 2.2 Ma (MSWD = 0.79). All quoted ages and uncertainties are at 2σ and include propagation of systematic uncertainties according to the protocol of Horstwood et al. (2016).

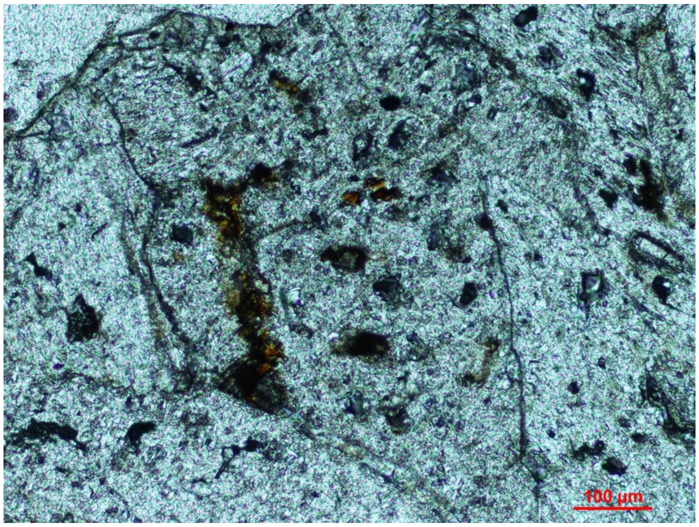
A full data-table is provided in DRx.

Sample information

<u>206/7a-2 well (2559.5 m) – Clair field: “Clair Basement”</u>

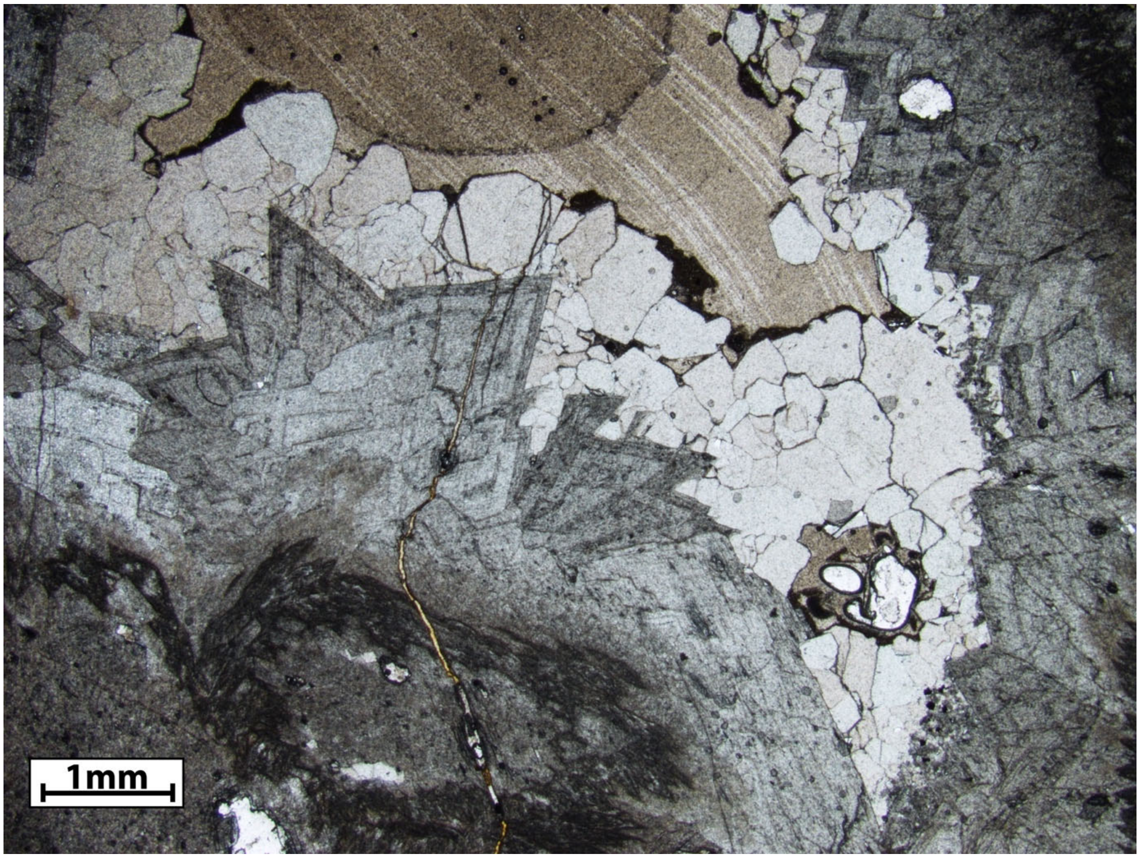


Sample of foliated granite cut by oil stained calcite-pyrite mineral fills in fracture connected to the structure shown in Fig 2a which also hosts earlier sediment and quartz cements. The calcite crystals carry numerous inclusions of oil suggesting that hydrocarbon was present at the time of calcite precipitation. See image below.

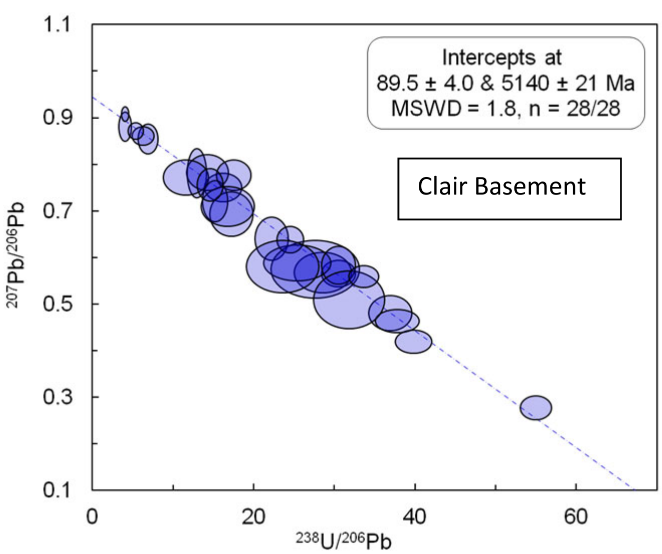


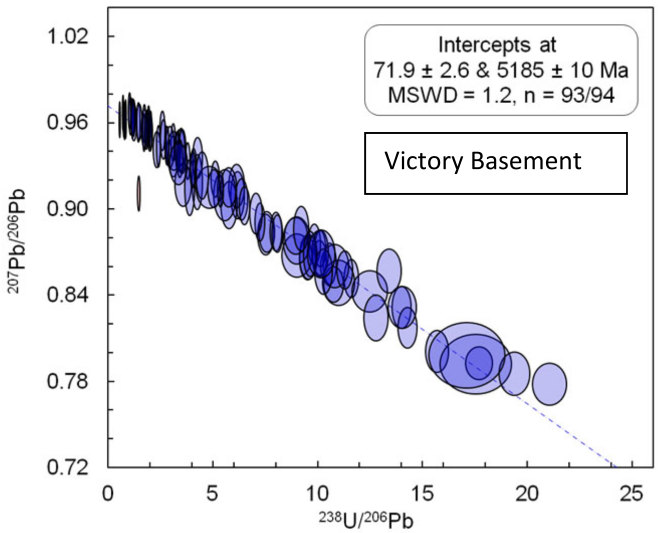
<u>208/27-2 well – near Victory Field: “Victory Basement”</u>

Granodioritic gneiss cut by quartz-calcite-pyrite filled fracture with large vug that originally hosted oil. The calcites here are hydrocarbon stained and zoned with numerous oil inclusions and are post-dated by quartz precipitation – see image below - the reverse relationship to that seen in the previous sample.


1mm

Results

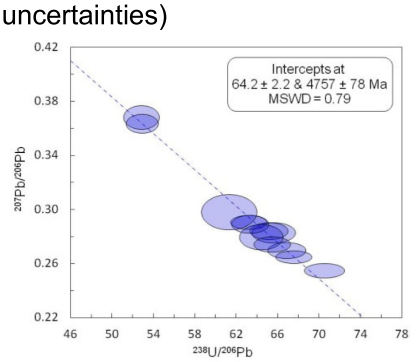

Intercepts at
89.5 ± 4.0 & 5140 ± 21 Ma
MSWD = 1.8, n = 28/28
Clair Basement
207Pb/206Pb
238U/206Pb
1.1
0.9
0.7
0.5
0.3
0.1
0
20
40
60



Sample	Age (lower intercept)	2s	Y-Int (207Pb/206Pb)	2s
Clair	89.5	4.0	0.944	0.013
Victory	71.9	2.6	0.972	0.002

Analytical Conditions

Laboratory & Sample Preparation	
Laboratory name	NERC Isotope Geosciences Laboratory
Sample type/mineral	Calcite
Sample preparation	In-situ in polished block
Imaging	None
Laser ablation system	
Make, Model & type	ESI/New Wave Research, 193UC
Ablation cell & volume	NWR TV2
Laser wavelength (nm)	193 nm
Pulse width (ns)	3-4 ns
Fluence ($J.cm^{-2}$)	~8 J/cm^2
Repetition rate (Hz)	10 Hz
Ablation duration (secs)	30 secs
Ablation pit depth / ablation rate	~45µm pit depth, measured using an optical microscope
Spot size (□m)	100 µm
Sampling mode /	Static spot ablation

pattern	
Carrier gas	100% He, Ar make-up gas combined ca. 50% along sample line.
Cell carrier gas flow (l/min)	0.6 l/min
ICP-MS Instrument	
Make, Model & type	Nu Instruments Attom SC-SF-ICP-MS
Sample introduction	Free air aspiration of desolvator
RF power (W)	1300 W
Make-up gas flow (l/min)	0.8 l/min Ar
Detection system	Discrete dynode MassCom ion counter
Masses measured	202, 204, 206, 207, 208, 232, 238
Integration time per peak	200μs (202, 204, 208, 232), 400μs (206), 1000μs (207, 238) 80 sweeps per integration
Total integration time per reading (secs)	0.30 seconds
Sensitivity / Efficiency (%, element)	~0.2 % for Uranium
IC Dead time (ns)	15 ns
Data Processing	
Gas blank	60 second on-peak zero subtracted
Calibration strategy	NIST 614 for Pb-Pb, WC-1 for Pb-U
Reference Material info	Primary: WC-1 254 +/- 6 Ma (2s) - Roberts et al., 2017 Secondary: Duff Brown 64.04 +/- 0.67 Ma (2s) - Hill et al., 2016
Data processing package used / Correction for LIEF	Nu Instruments TRA acquisition software, in-house spreadsheet data processing
Mass discrimination	$^{207}Pb/^{206}Pb$, $^{206}Pb/^{238}U$ normalised to reference materials
Common-Pb correction, composition and uncertainty	Unanchored (model 1) regressions in Tera-Wasserburg (Semi Total-Pb) plots.
Uncertainty level & propagation	Ages in the data table are quoted at 2s absolute and include systematic uncertainties, propagation is by quadratic addition.
Quality control / Validation	Duff Brown gave 64.2 ± 2.2 Ma (without propagation of systematic uncertainties) 

FLUID INCLUSION SAMPLES, PETROGRAPHY AND ANALYTICAL METHODS

The samples

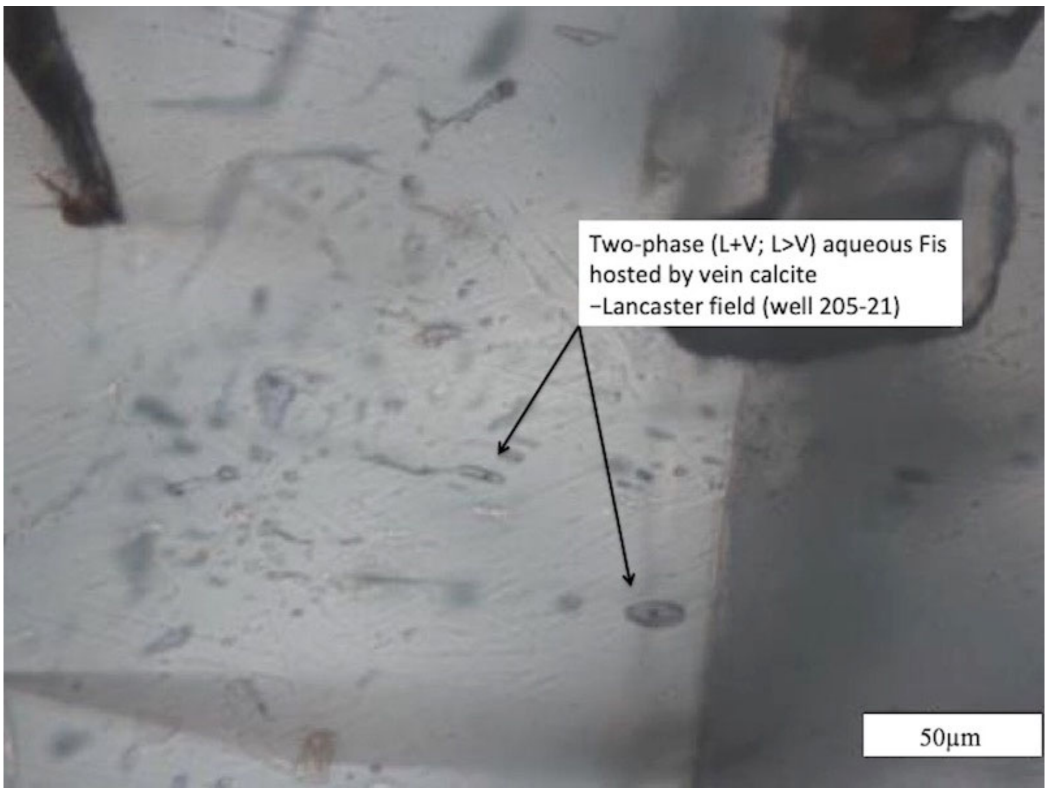
Four fracture-hosted hydrothermal fills of calcite (3) and quartz (1), linked to brittle deformation (affecting both basement and local Devonian and Jurassic cover rocks), were subjected to fluid inclusion studies to estimate the temperatures of mineral precipitation. One core sample from each of three wells, located to the west of Shetland, UK, were sampled for FI studies: Well 205/21-A (Lancaster field, sample no. Lan 205/21-A, calcite fracture fill cutting Rona (Jurassic) sandstone, depth 4435m); Well 206/7A-2 (Clair field, sample no. Clair 206/7A-2, a quartz and a calcite fracture fill cutting Precambrian basement granite, depth 2599.5m) and Well 206/8-16 (Clair field, sample no. Clair 206/8-16, Clair Group (Devonian), calcite fracture fill cutting sandstone, depth 1879.2m) see Table 1.

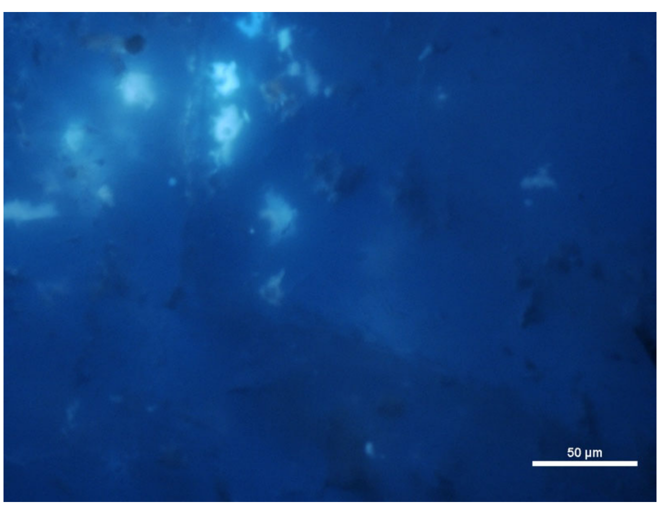
Sample	FI Host	T_H°C	Salinity (eq.wt.%NaCl)
Lancaster 205/21-A Rona Sst. (4435m)	Calcite	88-133 (n=7) (mean: 115)	1-3 (n=7) (mean:2)
Clair 206/8-16 Devonian Sst. (1879.2m)	Calcite	98-142 (n=4) (mean: 114)	5-10 (n=4) (mean: 6)
Clair 206/7A-2 Basement granite (2599.5m)	Quartz	214-218 (n=5) (mean: 217)	4-8 (n=5) (mean: 6)
	Calcite	138-146 (n=7) (mean:142)	5-13 (n=7) (mean:7)

Table 1. Sample descriptions and microthermometric data for each fracture mineral fill.

FI petrography

FI petrographic studies of the wafers, using a Nikon Eclipse E200 microscope revealed the dominant presence of two-phase aqueous fluid inclusions (i.e. Type 1) in all samples (Photomicrographs of Type 1). The Type 1 inclusions are two-phase (liquid + vapour; L > V) aqueous inclusions and are classified as fluid inclusion assemblages in each sample. Their degree of fill, F (F = vol. of liquid/ [vol. of liquid + vapour]) is ~0.70 (quartz) and ~0.90(calcite). They occur either as isolated individuals or in clusters and, as trails along annealed micro-fractures and are classified as being pseudosecondary to secondary FI. They range from c. 2μm to 30μm in longest dimension and display a range of morphologies that vary from irregular to ellipsoidal.





Left: Photomicrograph of fracture-hosted calcite containing two-phase (Liquid+Vapour; degree of fill ~0.90) hydrocarbon-bearing fluid inclusions displaying blue fluorescence in UV light. Sample Clair 206/8-16 (1879.2m).

FI microthermometry

Microthermometric analyses was performed using a calibrated Linkam THGMS 600 heating-freezing stage, mounted on an Olympus transmitted light microscope at the Geofluids Research Laboratory, National University of Ireland, Galway. Calibration of the stage was performed using synthetic fluid inclusion standards (i.e. pure CO_2 and water). Precision is ± 0.2°C at -56.5°C and ± 2°C at 300°C. The FI were subjected to heating and cooling cycles: ice formed during cooling of the inclusions to ~ -110°C and during subsequent heating, both the temperature of first ice melting (T_{FM}) and the temperature of last ice melting (T_{LM}) were recorded. The recorded T_{FM} values of c. -20.8°C equate to the eutectic melting point of the system NaCl-H_2O (Shepherd *et al.* 1985). The T_{LM} values were used to calculate salinity as equivalent weight % NaCl (eq. wt.% NaCl) after Bodnar (1993). Subsequent heating of the FI, facilitates the measurement of the temperature of homogenisation (T_H) i.e. the temperature at which the liquid and vapour phases homogenise to the liquid phase (for L-rich two-phase FI like Type 1). T_H in general is the minimum trapping temperature at which the fluid was trapped as the fluid inclusion formed.

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