Supplementary Information for:

Near-surface Palaeocene fluid flow, mineralisation and faulting at Flamborough Head, UK: new field observations and U-Pb calcite dating constraints

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Methodology

Imaging

Back-scattered electron (BSE) and charge-contrast (CCI) images were taken at the British Geological Survey (BGS, Nottingham, UK), using a FEI QUANTA 600 environmental scanning electron microscope (ESEM). Samples were prepared as resin-impregnated polished sections and imaged as uncoated samples under low-vacuum conditions (130 Pa) with a working distance of 10 mm. BSE images were recorded using a solid-state (dual-diode) electron detector, with a 20 kV electron beam accelerating voltage, and beam currents between 0.1 and 0.6 nA,. CCI images were recorded using a FEI large-field gaseous secondary electron (electron cascade) detector, with 20 kV electron beam accelerating voltage, and beam currents of 1.2 to 4.5 nA. Cathodoluminescence imaging was undertaken at the BGS using a Technosyn 8200 MkII cold-cathode luminoscope stage attached to a Nikon optical microscope with long working distance lenses, and equipped with a Zeiss AxioCam MRc5 digital camera; vacuum and electron beam voltage and current were adjusted as required to generate optimum luminescence.

U-Pb

LA-ICP-MS calcite U-Pb dating results are tabulated in the supplementary table. U-Pb geochronology was conducted at the Geochronology and Tracers Facility, British Geological Survey, UK, using the method described in Roberts and Walker (2016) and Roberts et al. (2017). Instrumentation used was a Nu Instruments Attom single collector ICP-MS, coupled to a NWR193UC laser ablation system fitted with a TV2 cell. Ablation conditions were a 100 µm spot, ablated for 30 seconds, using a fluence of 6 J/cm^2 with a repetition rate of 10 Hz. A gas blank of 60 seconds was subtracted at the beginning of each run, and a washout of 5 seconds was allowed between each ablation. Standard sample bracketing was employed, using NIST614 glass (values of

Woodhead and Hergt, 2001) for normalisation of Pb-Pb ratios, and WC1 (254 Ma; Roberts et al., 2017) for normalisation of Pb-U ratios. ASH15D was run as a secondary reference material (2.964 ± 0.009 Ma; Perach Nuriel personal communication, 2020) during two sessions, and provided ages of 2.81 ± 0.10 and 2.93 ± 0.12 Ma. DuffBrown Tank (64.04 ± 0.67 Ma; Hill et al., 2016) was run as another secondary reference material during two sessions, and provided ages of 64.6 ± 1.0 and 66.7 ± 1.7 Ma. Data are reduced using the time-resolved-analysis function in the Nu Attolab software, and an in-house excel spreadsheet. Uncertainty propagation is based on the fundamentals of Horstwood et al. (2016), and age uncertainties are quoted as ± α/β, where α is without systematic uncertainties, and β is with systematic uncertainties. No common lead correction is made; ages are determined from lower intercepts on a Tera-Wasserburg plot. All regressions are unanchored as the spread in data permits assessment of the upper intercept accurately.

Laboratory & Sample Preparation	
Laboratory name	Geochronology & Tracers Facility, NERC Isotope Geosciences Laboratory
Sample type/mineral	Calcite
Sample preparation	Polished thin sections
Imaging	Optical along with some minor CL and CCI.
Laser ablation system	
Make, Model & type	ESI/New Wave Research, UP193UC
Ablation cell & volume	NWR TV2
Laser wavelength (nm)	193 nm
Pulse width (ns)	4 ns
Fluence (J.cm^{-2})	~6 J/cm^{-2}
Repetition rate (Hz)	10 Hz
Spot size (m)	100 μm
Sampling mode/ pattern	Static spot
Carrier gas	100% He, Ar make-up gas from DSN-100 combined using a Y-piece 50% along sample line.
Ablation duration (secs)	30 secs
Cell carrier gas flow (l/min)	0.7 l/min
ICP-MS Instrument	
Make, Model & type	Nu Instruments, Attom, SC-ICP-MS
Sample introduction	Ablation aerosol
RF power (W)	1300 W
Make-up gas flow	0.7 l/min Ar
Detection system	Single Mascom SEM
Masses measured	202, 204, 206, 207, 208, 232, 238

Integration time per peak (ms)	Dwell times of 200 μs to 1000 μs per peak
Total integration time per reading (secs)	0.35 sec
Sensitivity/ Efficiency (%, element)	~0.2% U
IC Dead time (ns)	11 ns
Data Processing	
Gas blank	30 second on-peak zero subtracted
Calibration strategy	NIST614 for Pb-Pb ratios, WC-1 for $^{206}Pb/^{238}U$ ratio
Reference Material info	NIST614 (Woodhead and Hergt, 2001) WC1 (Roberts et al., 2017) ASH15D (Perach Nuriel pers. Comm. 2020) DuffBrown Tank (Hill et al., 2016)
Data processing package used / Correction for LIEF	In-house spreadsheet data processing after initial signal integration using Nu Instruments TRA software. No LIEF correction (mean of uncorrected ratios used)
Mass discrimination	Standard sample bracketing
Common-Pb correction, composition and uncertainty	None applied. Ages calculated from regressions used in Tera-Wasserburg plots.
Uncertainty level & propagation	Ages are quoted at 2σ absolute, propagation is by quadratic addition. Excess variance of reference material propagated into sample data. Systematic uncertainties include age uncertainty of reference material.
Other information	

References

Hill, C.A., Polyak, V.J., Asmerom, Y. and P. Provencio, P., 2016. Constraints on a Late Cretaceous uplift, denudation, and incision of the Grand Canyon region, southwestern Colorado Plateau, USA, from U-Pb dating of lacustrine limestone. Tectonics, 35(4), pp.896-906.

Horstwood, M.S., Košler, J., Gehrels, G., Jackson, S.E., McLean, N.M., Paton, C., Pearson, N.J., Sircombe, K., Sylvester, P., Vermeesch, P. and Bowring, J.F., 2016. Community-derived standards for LA-ICP-MS U-(Th-) Pb geochronology–Uncertainty propagation, age interpretation and data reporting. Geostandards and Geoanalytical Research, 40(3), pp.311-332.

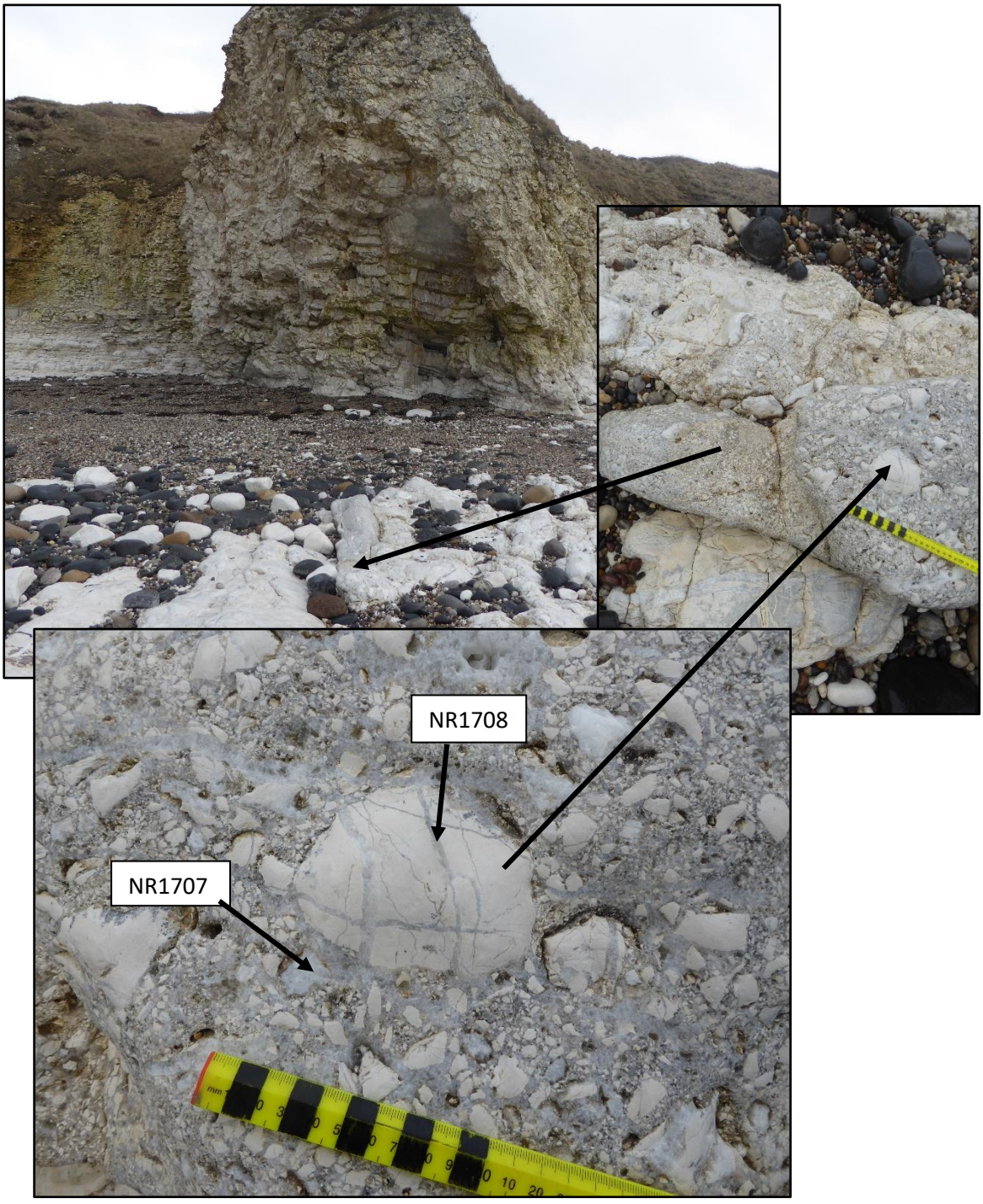
Roberts, N.M., Rasbury, E.T., Parrish, R.R., Smith, C.J., Horstwood, M.S. and Condon, D.J., 2017. A calcite reference material for LA-ICP-MS U-Pb geochronology. Geochemistry, Geophysics, Geosystems, 18(7), pp.2807-2814.

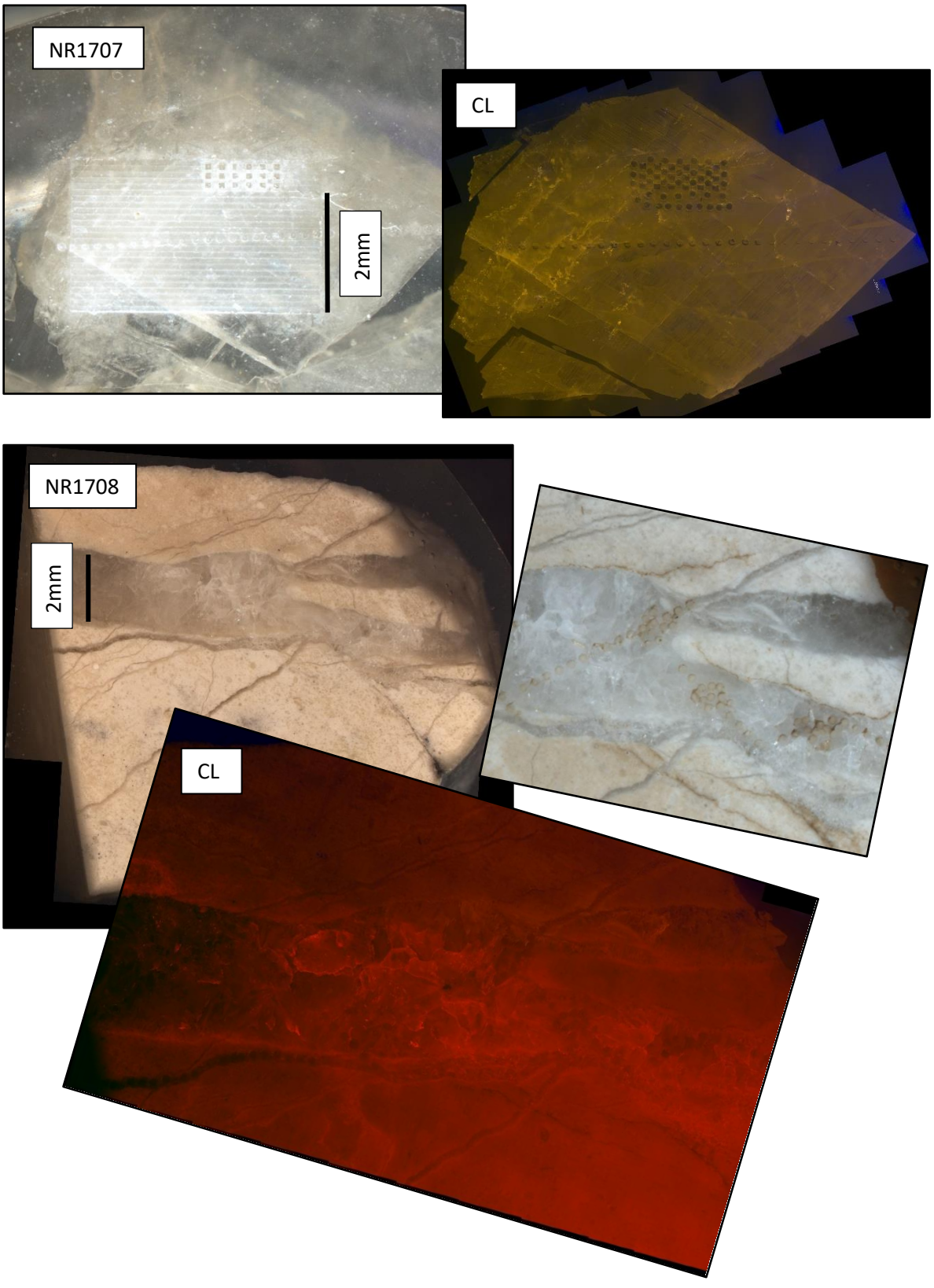
Roberts, N.M. and Walker, R.J., 2016. U-Pb geochronology of calcite-mineralized faults: Absolute timing of rift-related fault events on the northeast Atlantic margin. Geology, 44(7), pp.531-534.

Samples

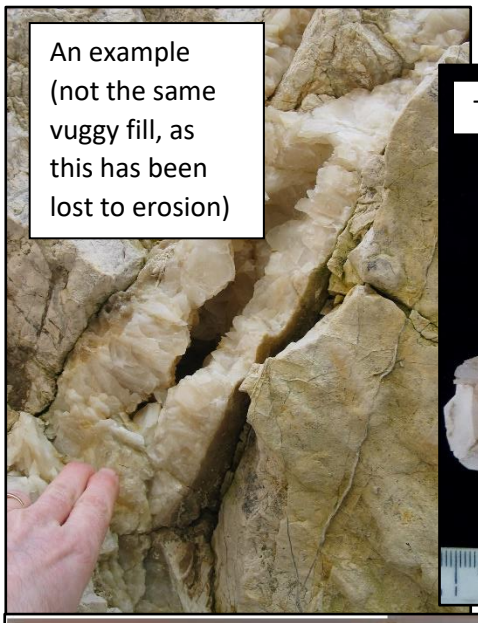
NR1707 - Vein cement from hydraulic breccia, hosted within the brecciated zone between Frontal Fault North and Frontal Fault South. Located on the foreshore.

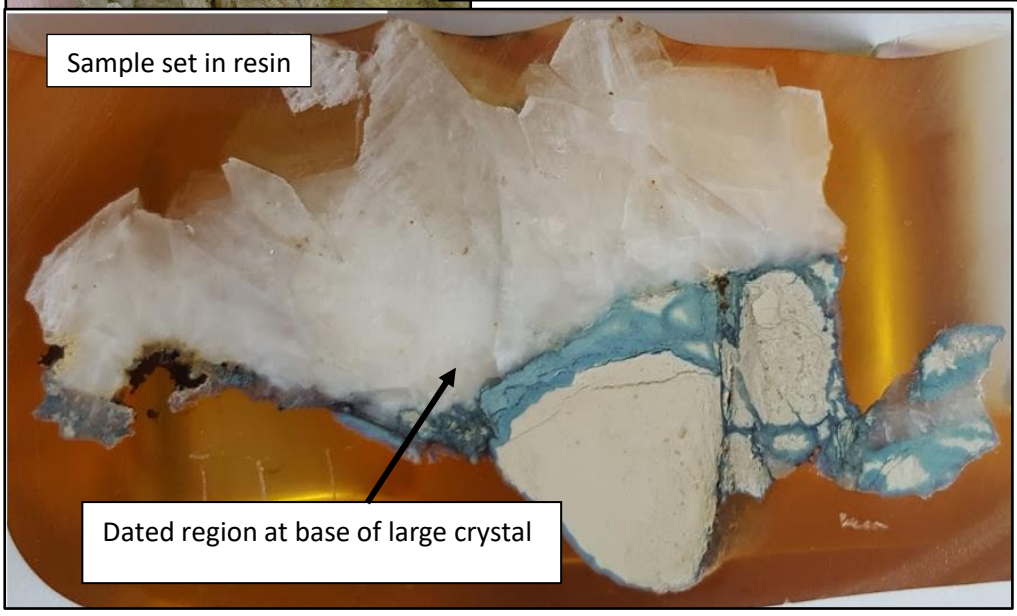
NR1708 - Vein cement from hydraulic breccia that is hosted within a rounded pebble of chalk, hosted within the brecciated zone between Frontal Fault North and Frontal Fault South. Located on the foreshore.



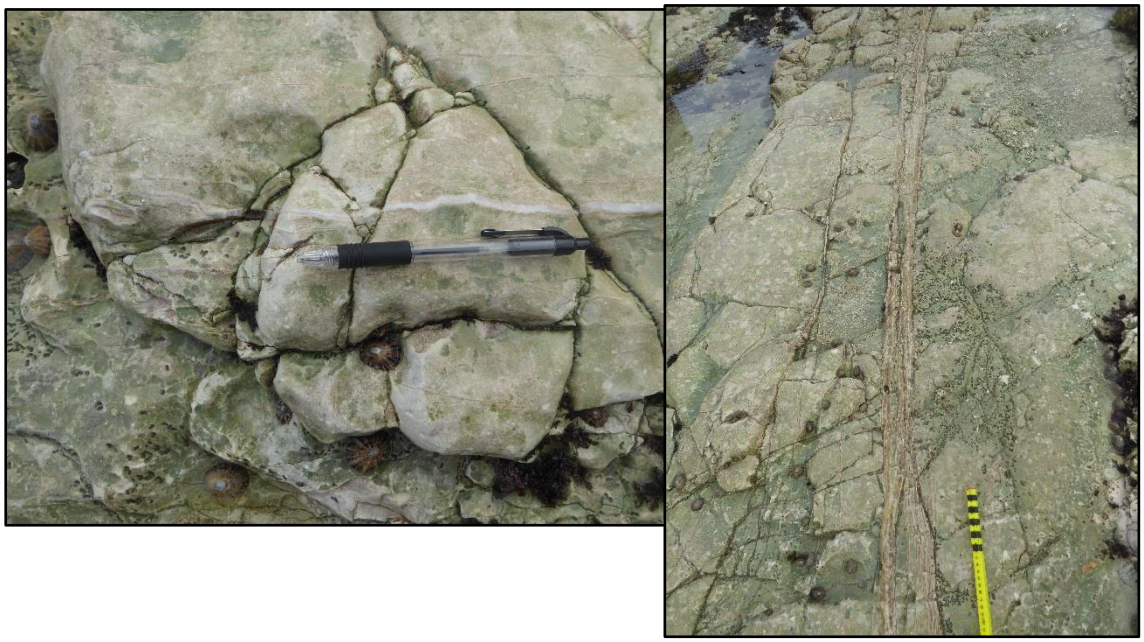

NR1707
2mm
CL
NR1708
2mm
CL

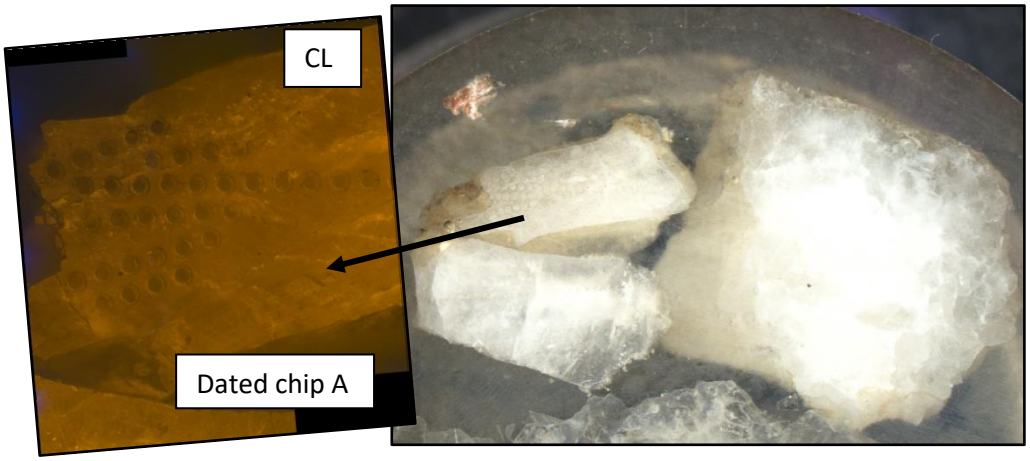
CJ1a - Large vuggy crystal within a tensile mode 1 vein hosted within the brecciated zone between Frontal Fault North and Frontal Fault South. Taken from the overhanging cliff.

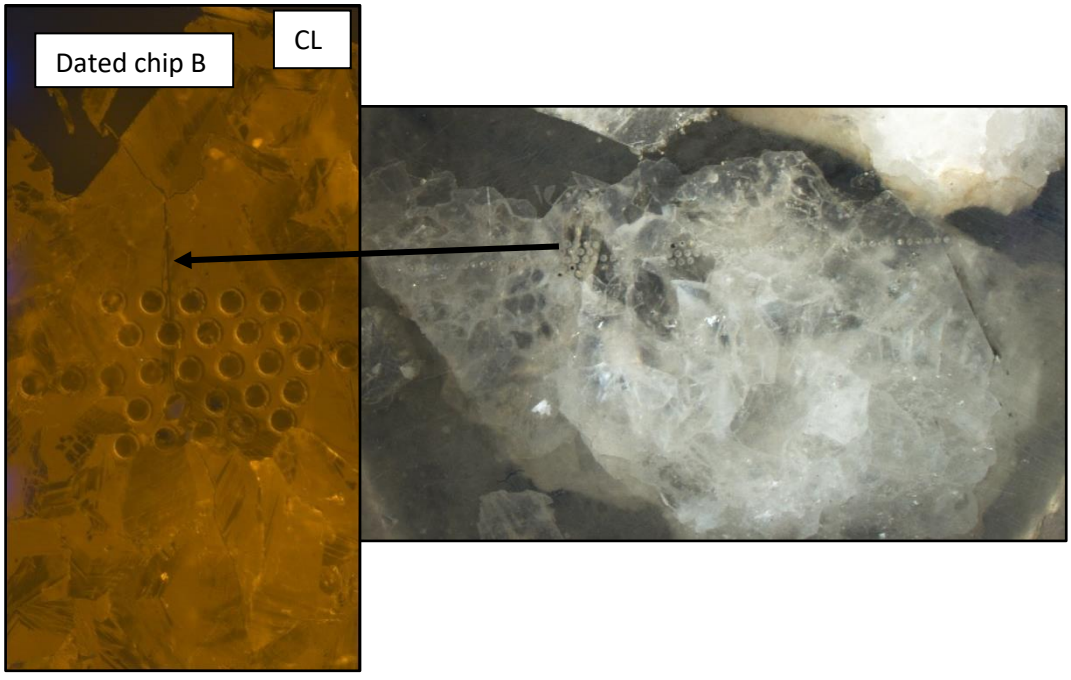




NR1709 - Tensile Mode 1 opening vein, orientated E-W, located at north side of bay, on the foreshore pavement.







NR1901 – Thin (<300 μm) vein cross-cutting slickenfibres adjacent to host rock. Slickenfibres formed on bedding plane during folding of beds.