Response to Reviewer 1

"This paper reports an important scientific contribution to the developing recalibration of the Cenozoic tectonic history of Britain and Ireland. As we currently understand this history, it is driven by two far-field processes, separated in time and only loosely linked kinematically: a) to the northwest, a mantle plume impinging on the developing rift zone destined to become the North Atlantic Ocean; b) to the south, later north-south shortening resulting from the Alpine and/or Pyrenean continental collisions. It is important to assign to one or the other driver the various Cenozoic structures in Britain. This new work by Roberts et al. demonstrates convincingly that calcite vein formation in the well-studied Flamborough Head Fault Zone dates from the Paleocene, and is therefore linked to the North Atlantic Igneous Province and to the opening of the North Atlantic, rather than to Eocene and later Pyrenean or Alpine events. The science in this paper is sound, and it is presented clearly both in the text and the figures. There are a number of mostly minor suggestions for improvement of the text in the attached annotated pdf. The only substantial suggestion is (at line 52) to discriminate between – as I understand it – the entirely Paleogene Pyrenean collision phase and the mainly Oligocene-Neogene Alpine collision phase."

We thank the reviewer for his positive comments on our study and manuscript.

All minor edits (only a dozen or so) that Nigel suggested on the pdf are adjusted in the revised version, including this comment on Line 52 where we now discriminate between the Pyrenean and Alpine collision.

Response to Reviewer 2

"General Comments: This paper is a well-done geochronology study investigating regional timing of faulting and fluid flow. The U-Pb carbonate geochronology method is fast becoming a well established method for directly dating faulting and fluid flow processes in the upper crust. This study uses this novel technique to provide the first absolute timing constraints in the region of interest. This is important because faulting in the Cretaceous chalks is an important process effecting reservoirs across much of Great Britain and the North Sea. This study therefore has the potential to provide a useful insight into the absolute timing and duration of fluid flow and faulting in the region with useful transferable applications to the petroleum and hydrogeology communities. This study is well conceived, uses appropriate methods, produces high-quality geochronology data that is well reported and documented."

We thank the reviewer for their positive comments. The rest of the review essentially asks for a more detailed structural study, and for more clarity over the samples and the locations of the samples/photos. As we discuss below, we have not attempted a major structural study, and therefore cannot include this. This was not the aim of this paper. We have made changes to the text and figures/photos so that it is easier to follow how things relate. We note that reviewer 1 did not have any issue with the presentation of our data.

"The interpretations are largely consistent with the data, although the structural history needs to be strengthened." Our aim was never to provide a new structural history that incorporated new structural mapping, as we know from previous work in the area that this would require a level of work akin to a good Masters project at least. As we discuss later on, we are aware that another group is working on revising the structural history and so we deliberately have not gone into further details here.

However, we have made revisions to the text and figures so that 'new' structural observations included here are properly constrained and caveated where necessary. "It also would have been nice if the study was broader in scale and scope."

No comment necessary.

"Sample documentation could be better represented in the paper."

We have improved this. (See later detail).

"The supplementary material is necessary and supports data in the main paper. Overall I think that this is a useful contribution to understanding the absolute timing of brittle faulting – a topic which is in its' infancy and with some additions (see below and in the annotated version of the manuscript), would make a nice regional geology study suitable for this journal."

"Specific Comments: 1. Structural data. I understand that the authors do not intend to make a detailed analysis of the structural evolution of the area (as stated in lines 158- 160), however I think that it would make this paper much stronger if you did include some structural data. That would make the linkage between the dates presented here and the structural interpretation much stronger and credible. It would also mean that you could interpret the ages relative to the structural setting with more confidence. I therefore suggest that you add stereonets of the orientation of your samples, the local structures and the regional stress regime (hopefully this shouldn't be too much work as you should already have all the data!)"

We understand the reviewer's point of view here. Firstly, the comments suggest that the limited structural information we present could be better presented so that readers can find the paper and lines of reasoning easy to follow. Secondly, and most critically, this is a very complicated area with multiple interpretations of the same structures in the literature. Although we made some structural observations, we are aware of another group working in the area, and are aware of them writing up their results (with students involved) at present. It would not therefore be prudent to usurp their work. To be honest, our aim was not to re-characterise the major structures, but to characterise the veining and fluid-flow to an extent that matched the scale of our geochronology, as this aspect of the geology has been much less studied. We know other groups have failed in the past at dating these structures at this particular site, and thus a very large project would be needed to get successful dates from a larger range of structures. Most of our conclusions do not rely on structural observations at the macro or regional scale. We thus do not see the need to add more detail on the regional structures. It is clear from the map that we are located in an E-W trending fault belt, and in our revised version we have avoided speculating too much about motion along this fault belt, or kinematics that created or reactivated it.

Stereonets of samples – A cement in a breccia has no orientation, and a single vug in a vein in a chaotic damage zone has no useful orientation - these are hosted in the E-W trending frontal fault. One other sample is also an E-W trending vein. We feel that adding a stereonet with two E-W trending fault/fracture planes, one vertical and one sub-vertical, is not really going to add much to the paper. The sample from the fold only dates post-folding veining, and thus we do not really discuss the origin of the folding; had we done this, we of course realise that more structural information on the fold orientation would be necessary.

"2. Geological setting: Throughout the writing could be more succinct and you could do a better job of describing the setting without interpreting- make more factual."

Without specific comments is it difficult to ascertain which parts are not succinct enough. We also note that the other review had no issues in this regard. We have not found examples of interpretation in the setting section. We state the timing that previous authors have constrained, these are for example, based on interpretation of seismic; however, that is not us adding interpretation into this section.

"A cross section would be useful."

Spectacularly detailed cross sections – some in 3D - are provided in Starmer 1995 and redrawn in Mortimore (2020); we now point this out. Without reassessing all of the observable structures, we do not feel it is necessary to redraw the same cross-section again.

"The structure is very linear, could you group together and discuss findings of authors rather than going through study by study."

We could, but we choose not to. The other reviewer had no problem here; also, each study generally discussed a different aspect or different methodology, so we feel that the evolution works.

"It would be useful to have a sentence at the end framing your study- why it is interesting and important."

We feel the end of the intro covers this: Here we present data from the Flamborough Head Fault Zone (FHFZ), which forms the southern boundary to the Mesozoic Cleveland Basin, and to which there is no consensus as to the timing and kinematic history. In this paper, we combine new field observations with U-Pb geochronology of calcite veins. Our dates present the first absolute timing constraints on deformation within the FHFZ, and are placed into context with new field observations pertinent to understanding the structural setting of associated fluid flow and fracture filling processes.

"Section 5 might be better coming before section 4, or potentially merged with it. When I initially read section 4, I wanted a lot of the details that are in section 5, so I think restructuring or merging would be beneficial."

Section 4 is very short, and generally describes macro-structures, before section 5 discusses smaller-scale structures. So we feel the order is fine.

"Some sample numbers on the figures would also be immensely helpful (see my comments below)."

Sample numbers are added to additional figure, and other relevant figures.

"3. Link between structural setting, sample description and ages. Initially it is quite challenging to link together the different structures, photos and samples. I think you do a good job in the supplementary material but in the figures in the text it is less easy to follow. See my comments below on the figures, adding sample numbers, more annotations and a little more context of how the different photographs link together (similar to in the supp material) would be helpful."

We have added an additional figure that shows the locations of the samples, as depicted in the supplementary figures. We thought about changing the order of figures, so they occur by locations; however, the text follows a logical narrative, through contractional structures, then extensional structures, then the types of vein-fill. The figures are ordered to match the text, and so we feel they also follow a logical narrative. We have added annotation to the figures to make it clearer what they are intending to show.

"4. Abstract – a little more information about the motivations of the study, why it is important and what the significance is would help to attract a broader audience.

We have added a sentence on why this is important.

"5. Throughout make sure that you always keep description/ data reporting and interpretation separate."

We have been through looking for examples of this. The only examples we can find are where we speculate on the timing of a structure when describing it, this is essentially a field observation. We feel it is OK to speculate something is likely the same age as something else based on its field observations, at the point of describing field observations. It is not really that different to saying structure X cross-cuts structure Y, and therefore X is younger. Yes it is interpretation, but it is generally accepted to make statements like this, and not save such an interpretative statement to later on. Regardless of this, we have moved the field observations so that they come after the dating results, thus they can be read with better context regarding the interpretation.

"6. Discussion Could you provide a (visual?) summary of the relative timing, cross cutting relationships, structural orientation and terminology of vein types? That might help focus your discussion and if you made a figure would be a great visual aid for the reader."

We have chosen not to do this. Each sample comes from a different area of veining, thus, no single figure can capture the cross-cutting relationships. With literally thousands of veins intersecting the damage zone, it would not be an easy task to capture this in a figure and do the outcrop any justice.

"The discussion is OK but you could be a little more definitive about interpreting the timing and sequence of compressional, extensional and strike-slip faults."

We have moved a couple of sentences around, so hopefully this is clearer. Given the limited scope of the structural study carried out here, we also feel that it would be dangerous to be too definitive. Our work sets that scene for further investigations.

"You could think more about the limitations of your dataset- you have only analysed a few samples, if you broadened out the study it might be possible to fully interpret the timing of the different structures and understand how the regional stress regime has changed through time. It would be interesting to make some comment about how these different structures might have formed and what overall stress regime you would need in order for the different structures to form. Addition of some structural data might help you be a little more definitive. What about pore fluid pressure and interaction between faulting and fluid flow?"

We feel these are rather general review comments. We feel our discussion already discussed the limitations of the dataset, e.g. ". It should be noted that we cannot rule out that fluid-flow and tensile fracturing may have extended to even younger dates than our study implies."

We are not sure what the reviewer means by broadening out the study. Study a larger area, use different techniques?... These comments all seem to allude to a structural re-interpretation, which as we have already mentioned, was not our motivation. We do however point out that our results suggest this would be fruitful in terms of improving our regional understanding.

Regarding pore fluid pressure, here too we feel that given the limits of what is presented and the relatively narrow scope of our sampling, it would require undue amounts of speculation on our part to go into much detail about this. The preservation of sediment fills and open vugs is somewhat problematic for the generation of overpressures as this generally requires a sealing mechanism to occur. In essence, we feel that this issue falls outside of the scope of the present study.

"How likely is it that there has been multiple periods of extensional faulting – during the Triassic- Cretaceous and then later in the Paleocene as recorded here."

The Chalk host rock here is Cretaceous, and so we are not sure of the relevance of this question. The fault zones described here may overlie and reactivate an older region of basement faulting at depth, but since we do not attempt to provide new information on why the FHFZ formed, we have not discussed this in any detail. Nor do we feel – in the context of the present paper and its findings – that this is necessary.

"Likewise, do you think if you dated more veins that you would end up dating later Cenozoic (re)activation of compressional structures?"

No. We think the extensional faulting is younger than the folding, and we see no evidence for later reactivation of these structures. There is also little material to actually date the compressional structures, these require syn-folding or syn-thrusting slickenfibres, and these are not that common. Those that do occur appear to not contain enough U to allow dating. This is one of the joys of calcite dating!

"See additional comments on annotated PDF of manuscript"

"Comments on figures: Figure 1 Please add a key to geological units Consider adding a cross section"

See earlier comment on cross section. Key added.

"Figure 2: Please add some structural data (see comments above)- produce stereonets of the orientation of veins related to the major structures. b) and c) could do with some additional annotation – show where veins are and clearly annotate sample locations d) it is not clear why you have drawn the arrows on the vug- perhaps a slightly zoomed out image would be more useful for demonstrating that sense of motion."

See previous comment on steronets and structural data. The relationship between veining and major structures is described perfectly clearly in the text. We have added additional annotation to the figures. The arrows show the extension direction (Mode 1), we have labelled this.

"Figure 3: a) scale? What evidence is there for the sense of motion drawn in the images? c) Annotations are not clear of folded strata. d) would an additional image taken perpendicular to this one be useful to showing the fold? Throughout the veins could be better annotated and any analysed samples clearly marked."

Offset beds show the sense of motion. We have added further annotations. There are no samples from this locality.

"Figure 4: How does fig. 4 relate to fig. 3? How do a) and b) relate to each other? Close up of gouge would be useful in b) Clearly label sample labels on analysed samplesare d) e) and f) all the same sample?"

Sample is labelled on figure 2. The first picture is replaced with another that is a better close-up of the gouge material.

"Figure 5: Link back to figure 2 to show where these samples are located Add sample numbers for analysed samples Some closer photographs of textures would be helpful."

These are all from the foreshore in front of the frontal faults, this is now stated. No samples came from these outcrops.

”Figure 6: More annotations needed Show where these photographs are on previous photos Add sample numbers for analysed samples.”

No samples came from these outcrops. Photos are from the damage zone of the Frontal Faults, this is now stated. Annotation added.

“Figure 7: Add sample numbers More annotations needed F) missing scale.”

Photos are not related to samples, scale fixed.

“Figure 8: The geochronology data and TeraWasserburg plots are good quality- well done!”

“Ideas for additional figures: 1. Figure clearly showing stereonets with: a) Orientation of main faults b) Orientation of your slickenfibres and veins with respect to these faults. c) You could link to stress analysis done by previous workers (Sanderson and Peacock)? 2. Cross section 3. Better way of linking field photographs (more like you have done in the supplementary material), that is a much clearer way to show how the samples relate to the structures and how each photograph relates to one another. 4. Interpretational diagram synthesising the interpreted vein genesis based on previous work and your ages. This would be a useful visual sum-up of all your data. Supplementary material Excellent presentation of methods and data. The only addition could be Concordia plots of secondary standards (Duff Brown and Ash 15) and reproducibility quoted as a %. Please also note the supplement to this comment: https://www.solidearth-discuss.net/se-2020-73/se-2020-73-RC2-supplement.pdf”

Our previous responses cover these comments.

We have been through the attachment and made minor alterations to the text where we saw room for improvement.

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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Abstract. We present new field observations from Selwicks Bay, NE England, an exposure of the Flamborough Head Fault Zone (FHFZ). We combine these with U-Pb geochronology of syn- to post-tectonic calcite mineralisation to provide absolute constraints on the timing of deformation. The extensional Frontal Fault zone, located within the FHFZ, was active at ca. 63 Ma, with protracted fluid activity occurring as late as~~as young as~~ ca. 55 Ma. Other dated tensile fractures overlap this timeframe, and also cross-cut earlier formed fold structures, providing a lower bracket for the timing of folding and compressional deformation. The Frontal Fault zone acted as a conduit for voluminous fluid flow, linking deeper sedimentary units to the shallow sub-surface, potentially hosting open voids at depth for a significant period of time, and exhibiting a protracted history of fracturing and fluid-flow over several million years. Such fault-hosted fluid pathways are important considerations in understanding chalk reservoirs and utilisation of the sub-surface for exploration, extraction and storage of raw and waste materials. ~~.~~Most structures at Selwicks Bay may have formed in a deformation history that is simpler than previously interpreted, with a protracted phase of extensional and strike-slip motion along the FHFZ. The timing of this deformation overlaps that of the nearby Cleveland Dyke intrusion and of regional uplift in NW Britain, opening the possibility that extensional deformation and hydrothermal mineralisation at Selwicks Bay are linked to these regional and far-field processes during the Palaeocene.

1 Introduction

Faulting of sedimentary basin fills in the subsurface is an important process in producing structurally constrained aquifers and reservoirs, as well as providing potential conduits and barriers to fluid resource migration and accumulation. Fault- and fracture-hosted infill and mineralisation allow us to assess the character and scale of along-fault fluid-migration. Maintenance of open fractures is an increasingly recognised phenomenon in faults formed in the shallowest parts of the crust down to depths of 1-2 km (e.g. Wright et al. 2009; van Gent et al. 2010; von Hagke et al. 2019). Open or partially open fractures can be propped open and preserved in the subsurface when they become infilled by wall rock collapse breccias, water-borne sediments and/or hydrothermal mineralisation (e.g. Walker et al. 2011; Holdsworth et al., 2019, 2020). These so-called fissure systems have the potential to act as significant channelways for the migration and storage of subsurface fluids such as water, hydrocarbons or geothermal fluids, and in carbonate aquifers, can also act as pathways for the development of larger dissolutional cond~~i~~uits and cave systems.

The absolute timings of fracture opening and fault displacement are critical to understanding how subsurface fluid migration evolves over time, and link individual fractures to the record of external tectonic deformation. Most sedimentary basins, whether ancient or currently active, lack direct chronological constraints on their structural history, and rely instead on the interpretation of stratigraphical and structural relations from field-data, or those imaged by geophysical means, e.g. seismic reflection data. Exposed faults can be directly dated if suitable geochronometers are preserved; recent methodological developments have broadened the range of such mineral chronometers. Clay minerals can be dated by K-Ar, Ar-Ar and Rb-Sr, but require fault gouge, and a meticulous analytical approach to generate robust dates (e.g. Viola et al., 2016). U-Th/He dating of hematite coatings (e.g. Ault et al., 2016), U-Th-Pb dating of hydrothermal monazite (Bergemann et al., 2018), Rb-Sr dating of feldspar (Tillberg et al., 2020) and Re-Os dating of hydrothermal sulphides (e.g. Dichiarante et al., 2016) are promising techniques that are also of use for faults and fault-hosted mineralisation of the right composition. In this paper, we utilise U-Pb dating of vein-filling calcite. Calcite is an ~~extremeny~~extremely abundant ~~material~~ mineral fill in brittle fractures and faults of wide-ranging host lithologies. It has been shown to be an effective chronometer that can be linked to the timing of hydrothermal minerali s~~z~~ation, fault slip and fold development (Roberts & Walker, 2016; Ring and Gerdes, 2016; Goodfellow et al., 2017; Nuriel et al., 2017, 2019; Beaudoin et al., 2018; Hansman et al., 2018; Holdsworth et al., 2019, 2020; Parrish et al., 2018; Smeraglia et al., 2019; Roberts et al., 2020).

In ancient sedimentary basin systems worldwide, many episodes of uplift and deformation are a consequence of tectonic inversion associated with the far-field effects of orogenesis. In the British Isles, the youngest of these events are~~is the~~ Cenozoic ~~(Neogene)~~and may be related to either the Palaeogene Pyrenean or Neogene ~~-~~Alpine orogeny, ~~which is~~both of which have been linked to major geological structures exposed across Southern ~~Britain~~ England (e.g. see Chadwick, 1993; Blundell, 2002; Parrish et al., 2018), but may also have led to deformation as far north as Yorkshire, and offshore in the Southern North Sea (Ziegler, 1989). Here we present data from the Flamborough Head Fault Zone (FHFZ), which forms the southern boundary to the Mesozoic Cleveland Basin, and for~~to~~ which there is no present consensus as to the timing and kinematic history. In this paper, we combine new field observations with U-Pb geochronology of calcite veins. Our dates present the first absolute timing constraints on deformation within the FHFZ, and are placed into context with new field observations pertinent to understanding the structural setting of associated fluid flow and fracture filling processes.

2 Geological Setting

The Mesozoic Cleveland Basin (Fig. 1a) located in East Yorkshire, northern England, has experienced inversion, the timing of which is poorly constrained. It is ~~generally~~ attributed by most authors to distant effects of the Pyrenean or ~~-~~Alpine orogeny (e.g. Starmer, 1995). The Jurassic-Cretaceous basin fills are bounded to the north and south by complex fault zones. To the south, the FHFZ is an east-east striking zone of brittle faults, which separates the Cleveland Basin from the Market Weighton Block ~~to the south~~ (Fig. 1a). Inland exposures of the fault zone are poor, and largely restricted to small quarries in Cretaceous C~~c~~halk; however, they can be mapped on the surface, and are visible on remotely sensed datasets (Farrant et al., 2015). In contrast, the coastline preserves excellent exposures of the faults and associated deformation. Flamborough Head (Fig. 1b) exposes several fault zones that have a complex structure and potentially a protracted history; these are the Bempton, Selwicks Bay, and Dykes End fault zones (Fig. 1b). The chalk at Flamborough Head is amongst the youngest exposed in Yorkshire, and comprises the Burnham Chalk Formation (Late Coniacian to Early Santonian) and the overlying Flamborough Chalk Formation (Santonian) (see Whitham, 1993; Mortimore, 2020).

The FHFZ is an E-W zone of brittle faults exposed at the coast at Flamborough Head, ~~and~~ extending inland for 30 to 40 miles (see Fig. 1a, and Farrant et al., 2015). The fault zone is linked with the Vale of Pickering Fault Zone (Kirby and Swallow, 1987), and has also been referred to as the Howardian Hill-Flamborough Fault Belt (Starmer, 1995). To the east, the fault zone is truncated offshore by the Dowsing Fault Zone, which forms the western margin of the Sole Pit Basin. The deformation of the Cretaceous C~~c~~halk rocks around Flamborough Head associated with some of the E-W faults has long been studied due to the excellent and structurally complex exposures preserved here (e.g. Phillips, 1829; Lamplugh, 1895; Kent, 1974; 1980; Kirby & Swallow, 1987; Peacock & Sanderson, 1994; Starmer, 1995, 2008, 2013; Rawson & Wright, 2000; Sagi et al., 2016).

Previous geological constraints on the timing of fault movements within the FHFZ come from the interpretation of seismic reflection data and sedimentological and structural analyses of several key outcrops (Jeans, 1973; Kirby and Swallow, 1987; Starmer, 1995). The offshore seismic interpretation of Kirby and Swallow (1987) indicates the existence of both steep faults that cut underlying Permian and Carboniferous strata at depth, and listric faults that detach within the Permian Zechstein strata. Faults on the northern and southern margins of the fault zone form a graben structure. Thickness changes of the Speeton Clay and Red Chalk have been interpreted as evidence that the northern fault zone (comprising the Bempton and Speeton faults; Fig. 1b) began movement in the early Cretaceous (Jeans, 1973; Neale, 1974; Kirby and Swallow, 1987). Kirby and Swallow (1987) concluded that an early stage of near-vertical normal faulting (early Cretaceous) produced the graben structure, which was then followed by a period of listric normal faulting, with both events occurring prior to the Late Cretaceous. Inversion of the former extensional structures, forming the ‘Shatter Zones’ at Bempton and Selwicks Bay, is inferred to have occurred at the end of the Cretaceous, and has been related to the more regional uplift, folding and inversion of the Cleveland Basin to the north forming amongst other structures, the Cleveland A~~a~~nticline (Fig. 1a, Kirby et al., 1987).

Peacock and Sanderson (1994) conducted a detailed investigation of the orientation and displacements of faults exposed around Flamborough Head, covering some 1340 individual structures. They interpret their data as indicating that sigma1 during faulting was sub-vertical, with extension occurring sub-horizontally in all directions, and that complex relationships existed between sigma2 and sigma3. Based on oblique-slip kinematics they suggested that a sub-horizontal sigma3 developed over time in a dominantly NNW-SSE direction. These authors also briefly describe the existence of contractional structures, namely oblique or reverse displacements on some fault surfaces, with a NNW-SSE contraction direction. Brecciation and veining are pervasive at Selwicks Bay, and Peacock and Sanderson (1994) tentatively suggest that both were related to the contractional event. They do not, however, present clear evidence for whether contraction preceded or followed extension.

Starmer (1995) produced a deformation history of the chalk at Selwicks Bay based on detailed mapping and structural analyses in onshore exposures of chalk; he describes four phases of deformation (D1 to D4). D1 produced folds with NNW-SSE axes and bedding plane-parallel shears, with an ENE-WSW to E-W shortening~~compression~~ direction. Subsequent D2 deformation was attributed to extension in an E-W direction, and the formation of tensional extensional fractures. D3 started with E-W directed flexure of the strata, and some strike-slip faulting. Once the folds~~ing~~ had tightened, thrusts with top-to-the-S to -SSE shear sense directions cut through the strata. Dextral strike-~~-~~slip~~shearing~~ at the same time suggested a ~~an element of~~ transpressional strain~~alongside the dominant N-S compression~~. D4 was interpreted as a complex phase of extension-transtension, first with E-W extension allowing N-S structures to activate, and followed by a N-S component of extension. Starmer (1995) links these events to ‘Laramide’ (late Maastrichtian to early Palaeocene) compression (D1), ‘Laramide’ extension (D2), Alpine (Oligocene) compression (D3) and post-Alpine extension (D4).

Sagi et al. (2016) studied the exposures at both Selwicks Bay and Dykes End (see Fig. 1b), analysing the fault density and connectivity in particular, and the relationship of these to fluid-flow. These authors describe numerous occurrences of dilational and contractional jogs occurring along the fault planes, exhibiting textures that include pressure solution styolites and coarse-crystalline calcite vein-fill. At Selwicks Bay, Sagi et al. (2016) focused on two large, steeply-dipping ENE-WSE normal faults that are a distinctive structural feature (the Frontal Faults of Starmer, 1995), related to folding and intense metre scale zones of intense veining and brecciation in the chalk wall rocks. These authors describe the damage zones associated with this set of faults (the Selwicks Bay ‘Shatter Zone’) and show that they are 4 to 5 m wide in the footwall, but less than 1 m wide in the hanging-wall. These brecciated damage zones are where the highest intensity of veining occurs forming a highly interconnected, braided network of tensile calcite-filled fractures. This study showed that fluid connectivity was much higher in the damage zones of the faults (up to 60%) compared the surrounding wall-rock~~protolith~~ (less than 10%), i.e. that these faults unequivocally represented highly effective fluid conduits in the geological past.

Faÿ-Gomard et al. (2018) present a geochemical study of veining at Selwicks Bay, and describe a relative chronology of three different phases of calcite veining. They use clumped isotopes of carbonates to determine precipitation temperatures of ca. 60°C, and combined with carbon, oxygen and strontium isotope analyses, postulate that the fluids originate from the underlying Triassic Sherwood sandstone. These authors link the timing of veining to Late Mesozoic~~Cenozoic~~ to Cenozoic basin inversion, suggesting veining may have occurred in a pulsed manner ~~in occurrence with pulsed~~linked to phases of inversion; although in their figure, they utilise the burial history curve of Emery (2016), correlating the veining with Oligocene-Miocene regional uplift.

Mortimore (2019) revisited the stratigraphy of the chalk exposed at Selwicks Bay, providing new stratigraphic and sedimentological logs for exposures north and south of the Frontal Faults. Mortimore (2019) also re-evaluated both micro and macro–scale structures and sedimentological features exposed at Selwicks Bay, questioning whether many of those exposed are a result of syn-sedimentary slumping and downslope displacement, rather than being purely tectonic processes.

3 Methodology

Fieldwork focussed on examples of calcite mineralis~~z~~ation associated with folds, fractures and faults in the well-exposed Selwicks Bay (Fig. 1c). ~~The chalks here are amongst the youngest exposed in Yorkshire and include the older Burnham Chalk Formation (Upper Turonian to Coniacian) overlain by the younger Flamborough Chalk Formation (Santonian to Campanian) (see Whitham, 1993).~~ Several samples of calcite mineralis~~z~~ation were collected for U-Pb dating purposes, with additional material collected from some fracture fills in order to understand the geological context of fracture-filling processes. Thin sections from these samples were studied optically in order to characterise the mineralogy, structural setting and – where possible – the sequence of fracture filling in each sample.

U-Pb geochronology was conducted at the Geochronology and Tracers Facility, British Geological Survey, UK. Samples were analysed using polished epoxy blocks/slabs. The instrumentation used was a New Wave Research 193UC excimer laser ablation system fitted with a TV2 cell, coupled to a Nu Instruments Attom single collector inductively coupled plasma mass spectrometer (ICP-MS). The method follows that described in Roberts et al. (2017). Laser parameters were pre-ablation conditions of 150 µm static spots fired at 10 Hz with a fluence of ~8 J/cm^2 for 2 seconds, and ablation conditions of a 100 µm spot, fired at 10 Hz with a fluence of ~8 J/cm^2 for 30 seconds. A 60 second background is taken before every set of standard-bracketed analyses, and a 5 second washout is left between each ablation. Data reduction uses the Time Resolved Analysis function of the Nu Instruments Attolab software, and an E~~e~~xcel spreadsheet. Isoplot v4 (Ludwig, 2011) is used for calculation and plotting of ages. Uncertainty propagation follows the recommendations of Horstwood et al. (2016), with final~~ and all~~ dates including~~e~~ propagation of systematic uncertainties. The carbonate material WC-1 (254 Ma; Roberts et al., 2017) was used as the primary reference material, and Duff Brown Tank (64.04 Ma; Hill et al., 2016) and ASH15D (2.96 Ma; Perach Nuriel pers.

Comm. 2020) were used as validation materials. The pooled result of all Duff Brown analyses yields a lower intercept age of 65.4 ± 1.2 Ma, and the pooled result of ASH15D yields a lower intercept age of 2.88 ± 0.08 Ma.

4 ~~Field observations and~~ O~~o~~utcrop settings of samples

It is not our intention here to provide a detailed kinematic analysis of faulting in the region. I~~, i~~nstead, it is our objective to simply provide the context for our new U-Pb dates in terms of the general movement history of the fault zones and the associated hydrothermal mineralisation.

Our sampling comes from three outcrop locations (Fig. 1c); all photographs in the following sections relate to these three locations and a fourth that wasn't sampled. Location 1 is the damage zone between the two E-W striking 'Frontal Faults' (Frontal Fault North, and Frontal Fault South), of Starmer (1995), also termed the Intensely Brecciated Zone (IBZ) by~~of~~ Sagi et al. (2016).

~~Three samples (NR1707, NR1708 and CJ1) come from the brecciated regions associated with a sub-parallel set of steeply northward dipping normal faults exposed at the south of Selwicks Bay (Fig. 2a; the E-W 'Frontal Faults' of Starmer (1995), and the Intensely Brecciated Zone (IBZ) of Sagi et al. (2016).~~ The combined displacement across these faults has been estimated as ~20 m based on stratigraphic offsets (Rawson and Wright, 2000; Mortimore, 2019), with downthrow to the north. ~~Either side of the fault zone – and particularly in the hangingwall region – cm- to m-scale drag folding of the beds in the chalks clearly demonstrates this sense of motion (Fig. 2a).~~ The two faults separate a 4-5 m wide zone of highly calcite veined, variably misoriented and brecciated chalk (Figs. 2a-2d, 3a-3d~~d~~). The areas of breccia are highly variable in their development – some smaller examples up to 20 cm wide are fairly constant in thickness and are bounded by well-defined planar fracture surfaces (Fig. 3~~2~~b~~d~~), whilst others are more irregular, with diffuse margins, varying between a few cm to more than 1.5 m across. As noted by Sagi et al. (2016), many~~main~~ veins in the brecciated panel between the two bounding faults show geometries consistent with tensile (M~~m~~ode I) opening during normal faulting (Fig. 3~~2d~~b), with the development of well-defined median lines and, in places, open vuggy cavities suggesting syntaxial mineralis~~z~~ation into large open voids (Woodcock et al., 2014). Three samples comes from this damage zone. CJ-1 is from coarse-grained (up to 10cm) calcite grown in an open vug within the cliff (similar to Fig. 3b). NR1707 and NR1708 are from the calcite cement within the damage zone breccia, located on the foreshore approximately 20 m from the main cliff. NR1707 is from the main matrix cement, and NR1708 is from a vein of calcite cement that is located within a chalk of pebble (Fig. 2b-2d)

Location 2 is the region of folding in the middle of the bay, approximately 30 m north of the Frontal Faults and Location 1. The sample NR1901 comes from a tight synformal fold (Fig. 2e, 4c). Here, a metre-scale, close to tight, southward verging antiform-synform pair is developed and is closely associated with at least two top-to-the-S low to moderately N dipping thrust faults (Fig. 4c). The exposed synformal fold hinge reveals bedding-parallel calcite slickenfibres oriented at high angles, oblique to the fold hinge (Fig. 2f-2g, 4d) consistent with the operation of oblique flexural slip processes during folding (e.g. Holdsworth et al., 2002).

The final~~Another~~ sample, NR1709 comes from an E-W steeply dipping tensile calcite vein in the ~~heavily~~ densely fractured natural pavement close to the base of North Cliff (Fig. 2h-2i;~~1c~~ Loc. 4). The structural setting of these veins is seen in the cliffs ~~immediately along strike and to the west~~ to the west about half way between Localities 2 and 4 where a steeply S dipping normal fault with dip-slip slickenlines is seen offsetting an earlier low angle thrust fault with a cm-scale, close to tight southward verging antiform in its immediate hangingwall (Fig. 4~~3~~a; Loc. 3). Close to the beach at the base of the cliff, ~~the~~ E-W subvertical calcite veins identical to those at Locality 4 are seen to be well developed in the immediate hangingwall of the normal fault and show a sense of obliquity consistent with the normal shear sense along the fault (Fig. 4~~3~~b), suggesting that they are the same age.

In the following sections we first provide the results of our U-Pb geochronology, and then, to understand the context of our new dates, we provide field observations and petrographic observations based on thin sections.

~~Linking statement to next section needed?~~

5 U-Pb Geochronology~~6~~ Results

Tera-Wasserburg plots of our new~~the resulting~~ U-Pb data are shown in Figure 5~~8~~. NR1707 yielded a lower intercept date of 63.9 ± 2.6 Ma (MSWD = 2.1); this date is from seventeen spots from one crystal. NR1708 yielded a lower intercept date of 63.4 ± 5.3 Ma (MSWD = 1.8); this date results from a traverse of one crystal comprising forty-nine spots. CJ1 is from a localised region of one large calcite crystal, towards its base; sixty-one spots yielded a date of 54.9 ± 3.1 Ma (MSWD = 1.5). ~~NR1709 yielded a lower intercept date of 56.2 ± 8.2 Ma (MSWD = 1.6 Ma); this result was obtained from two crystals, comprising fifty-one spots in total.~~ Two domains of NR1901 were calculated separately. The first domain comprising thin (<200 μm) layers of slickenfibre calcite yielded no reasonable date, as the data are dominated by common lead (see supplementary file). The second domain comprising a cross-cutting veinlet yielded a date of 58.8 ± 1.9 Ma (MSWD = 1.4); this date is from seventy-three spots. NR1709 yielded a lower intercept date of 56.2 ± 8.2 Ma (MSWD = 1.6 Ma); this result was obtained from two crystals, comprising fifty-one spots in total. The five successful dates provide a spread in crystallisation of nine million years, although taking uncertainties into account, this may be as small as three million years. The three samples from the Frontal Fault (NR1708, NR1709, CJ-1) do not overlap when considering their age uncertainties, indicating a protracted period of fluid-flow of several Myrs.

~~A final sample, NR1901 comes from a tight synformal fold some 40m N of the northern Frontal Fault (Fig. 1c). Here a metre-scale, close to tight, southward verging antiform-synform pair is developed and is closely associated with at least two top-to-the-S low to moderately N dipping thrust faults (Fig. 3c). The exposed synformal fold hinge reveals bedding-parallel calcite slickenfibres oriented at high angles, oblique to the fold hinge (Fig. 3d) consistent with the operation of oblique flexural-slip processes during folding (e.g. Holdsworth et al., 2002). The age of the folds relative to the normal movements along the Frontal Faults is unclear as no clear mesoscale cross-cutting relationships are seen, but the folds and thrusts cross cut by the normal faults at North Cliff are identical in style to those at this last locality. Thus, it is suggested that the main phase of extensional displacement and hydrothermal calcite mineralisation associated with the Frontal Fault Zone likely post-dates an earlier phase of generally top-to-the-S thrusting and folding.~~

6 Field Observations -~~5~~ Fracture fills and microstructure

~~Linking statement needed here – like we've got these ages and in order to understand their context we need to look at the field relationships in more detail.~~

The contractional and extensional phases of deformation seen in Selwicks Bay are associated with significantly different fault rocks and fracture fills.

6~~5~~.1 Contractional structures

The ~~earlier~~ low angle thrusts and folds are typically marked by narrow (<5cm thick) zones of incohesive crush breccia and gouge (Fig. 6~~4~~a, ~~and~~ 6~~4~~b), with gouges often best developed where thrust faults interact with clay-rich 'marly' interbeds in the chalk. Local gouge injections <1mm thick are seen cutting the wall rocks adjacent to thrusts (Fig. 6~~4~~b). Calcite ~~mineralization~~ mineralisation is largely limited to the development of slickenfibres along exposed thrust planes ~~(Fig. 4c)~~ and bedding planes around metre-scale folds (Figs. 2f, 6d)~~. 4d)~~. These slickenfibres show widespread evidence for crack-seal textures and are locally cross cut by later veinlets of structureless sparry calcite (Fig. 2g). The age of the folding relative to the normal movements along the Frontal Faults is unclear, as no clear mesoscale cross-cutting relationships are seen, but the folds and thrusts cross cut by the normal faults at ~~North Cliff~~Locality 3 are identical in style to those at this last locality. Thus, it is suggested that the main phase of extensional displacement and hydrothermal calcite mineralisation associated with the Frontal Fault Zone likely post-dates an earlier phase of generally top-to-the-S thrusting and folding.~~4e-4f).~~

6~~5~~.2 Extensional structures

The fracture fills associated with both the 'Frontal Fault' zone of Starmer (1995) and the small scale normal faults and associated veins elsewhere in Selwicks Bay are significantly different compared to the earlier contractional features.

Shear fractures have various orientations in the wall rocks, comprising small-offset (< 0.5m) normal faults with dip-slip slickenlines (Sagi et al., 2016). These are closely associated with steeply dipping to subvertical generally E-W trending calcite veins filling tensile (Mode I) fractures (e.g. Figs 3b-c~~2b, 3d~~, 7~~5~~a-c; the Group I veins of Faÿ-Gomord et al. 2018). The ~~F~~fills are predominantly fine to coarse-grained sparry calcite and commonly form as braided, up to 0.5 m wide zones of veins (e.g. Fig 3c-d~~2b~~) that resemble the "zebra rocks" described by Holland and Urai (2010) in low porosity limestones in Oman. Most individual veins have an average thickness of 1–2 mm, but the thickest can (locally) reach widths of up to 30 cm. Many veins are composite having more than one calcite fill with subtle differences in colour.

Breccia fills are mostly associated with the Frontal Fault zone (e.g. Figs. 2c-d, 3c-d). The majority are generally E-W to ENE-WSW trending, steeply dipping, with clasts dominated by chalk that are clearly derived from the host wall rocks, although differences in texture and colour of individual clasts relative to immediately adjacent wall rocks and other clasts indicate a degree of mixing and displacement from source. The breccias show every gradation from incipient crackle (Fig. 7a~~5a~~) through mosaic to chaotic textures (Fig.~~s~~ 2c, 7~~5~~b~~, c~~), with clasts becoming generally more rounded as the fill becomes chaotic (Woodcock & Mort, 2008). Importantly, the fills show very little evidence for shearing or attrition of clasts and closely resemble~~ collapse~~ breccias formed by wall rock collapse and infilling into open tensile fissures in near surface faulting environments (Woodcock et al., 2006; Holdsworth et al., 2019, 2020).

The breccia matrices are compositionally very variable. Some are clay rich ('marly') and darker coloured whilst the majority are lighter coloured with less clay and are well cemented by sparry calcite (the Group II veins of Faÿ-Gomord et al., 2018). Generally, E-W trending calcite veins essentially identical to those seen in the wall rocks are seen to both cross-cut breccia as well as being included as clasts in breccia or as earlier misoriented veins cross-cutting chalk clasts (Fig. 2d, ~~5~~7b). This might suggest that calcite minerali~~z~~sation, breccia formation and cementation were broadly contemporaneous processes.~~ Sample NR1707 in the current study is taken from a matrix cement, while NR1708 is from an earlier vein that cuts a chalk clast.~~ Many veins are composite having more than one calcite fill with subtle differences in colour; weathering on the foreshore reveals both ferroan calcite (stained red due to oxidation) and non-ferroan calcite (unstained) fills (Fig 7~~5~~c), implying changing fluid chemistry during the period of fracture-fill mineralisation.

A notable feature~~s~~ of the locally later tensile calcite vein fills (Group III veins of Faÿ-Gomord et al., 2018) is the widespread development of vuggy cavities (Figs. 3b~~2d~~ and 7~~5~~b); these are particularly widespread in the Frontal Fault zone. Their development implies that in the latter stages of vein filling at least, rates of mineral precipitation were reduced relative to fracture opening rates, implying that fractures remained open for protracted periods of time.~~ Sample CJ1 comes from one of these large vuggy vein fills.~~

Further evidence for the development of long-lived open fissures in the Frontal Fault zone comes from the preservation of brown-coloured marly breccias and sediment fills in tensile fissures (Figs. 8~~6~~a-d). These occur as sub-vertical features that both post-date and predate adjacent sub-parallel calcite veins (Figs. 8~~6~~a and 8b~~b~~, respectively) and in steeply inclined fissures that obliquely cross-cut adjacent veins (Fig. 8~~6~~c). More rarely, irregular subhorizontal zones of fine marly sediment fill the lower part of fractures that cross-cut earlier calcite veins, whilst the upper part of the cavity is filled with later calcite (Fig. 8~~6~~d). These sediments are crudely bedded and represent geopetal structures that consistently young upwards wherever they are found.

Thin sections reveal that the majority of calcite veins are syntaxial and sparry (Fig. 9~~7~~a). The marly breccias and sediment fills contain numerous fragments of wall rock chalk, earlier calcite vein fills and more exotic materials such as brown clays, chert, individual microfossils - including sponge spicules - and rounded grains of both quartz and glauconite (Fig. 9~~7~~b-d). The geopetal fills preserve striking examples of graded bedding (Figs. 9~~7~~a and 9~~7~~e) and cockade style minerali~~z~~sation textures (Fig. ~~7~~9f), with fine grained, graded suspensions of sedimentary grains floating in single crystals of calcite cement grown in perfect optical continuity with adjacent vein fills (Figs. 9~~7~~a, 9~~7~~e, and 9~~7~~f). The preservation of such features suggest that sedimentary material was transported by flowing fluids into open cavities connected to the surface and that cementation associated with contemporaneous hydrothermal minerali~~z~~sation ‘froze’ the finer materials in place before they were able to settle out of suspension (cf. Wright et al., 2009; Frenzel & Woodcock, 2014).

In summary, most, but not all of the calcite minerali~~z~~sation seen at Selwicks Bay is related to extensional structures that locally appear to post-date an earlier phase of cm to m-scale top-to-the-S folding and thrusting. Mineral veins are predominantly tensile and generally E-W trending and appear to be broadly contemporaneous with the development of calcite mineralized breccias along the Frontal Fault zone. The breccias preserve widespread textures consistent with wall rock collapse into open cavities rather than being the product of attritional cataclasis. The existence of long-lived open fissures is confirmed by the widespread preservation of vuggy textures and cockade-style calcite minerali~~z~~sation, together with the local development of marly sediment fills and geopetal structures. Based on the large amount of calcite minerali~~z~~sation – especially along the Frontal Fault zone, it is clear that substantial volumes of fluid flow have been localised along this fault zone during extension (Sagi et al., 2016).

~~6 Results~~

~~Tera-Wasserburg plots of the resulting U-Pb data are shown in Figure 8. NR1707 yielded a lower intercept date of 63.9 ± 2.6 Ma (MSWD = 2.1); this date is from seventeen spots from one crystal. NR1708 yielded a lower intercept date of 63.4 ± 5.3 Ma (MSWD = 1.8); this date results from a traverse of one crystal comprising forty-nine spots. CJ1 is from a localised region of one large calcite crystal, towards its base; sixty-one spots yielded a date of 54.9 ± 3.1 Ma (MSWD = 1.5). NR1709 yielded a lower intercept date of 56.2 ± 8.2 Ma (MSWD = 1.6 Ma); this result was obtained from two crystals, comprising fifty-one~~

~~spots in total. Two domains of NR1901 were calculated separately. The first domain comprising thin (<200 μm) layers of slickenfibre calcite yielded no reasonable date, as the data are dominated by common lead (see supplementary file). The second domain comprising a cross-cutting veinlet yielded a date of 58.8 ± 1.9 Ma (MSWD = 1.4); this date is from seventy-three spots. The five successful dates provide a spread in crystallisation of nine million years, although taking uncertainties into account, this may be as small as three million years. The three samples from the Frontal Fault (NR1708, NR1709, CJ-1) do not overlap when considering their age uncertainties, indicating a protracted period of fluid-flow of several Myrs.~~

7 Discussion

7.1 The timing of deformation at Selwicks Bay

The dates obtained from the five samples yield constraints on the timing of deformation at Selwicks Bay. NR1707 and NR1708 (Loc 1) are inferred to directly date the extensional phase of deformation (normal faulting) along the Frontal Fault zone, ~~(and FHZF)~~ as they are from regions of calcite veining and cemented collapse breccias. These samples provide overlapping ages of 63.9 and 63.4 Ma. CJ1 is also from the Frontal Front zone, but yields a younger age of 54.9 Ma that is outside of analytical uncertainty of the breccia samples. This younger date is from a relatively late large vuggy fracture fill. We cannot be certain whether this younger date reflects a ~~regionally~~ later fracture~~-~~ opening event, but there are no clear field or thin section relationships observed to suggest this. NR1709 (Loc. 4) has a large uncertainty, overlapping both the breccia and younger vuggy calcite from the Frontal Fault. The date indicates that fracture opening at the northern part of Selwicks Bay overlaps that of the Frontal Fault in the southern part of the bay. The dated late veinlet within sample NR1901 (Loc. 2) overlaps the dates of the other samples (except NR1707). Since this veinlet cross-cuts the flexural folding-related slickenfibre growth, this date provides a lower boundary for the timing of the folding and associated ~~co~~contractional/transpressional deformation.

7.2 Implications for chalk-hosted fluid-flow

Chalk is an important aquifer for groundwater, particularly in parts of Britain and surrounding countries in Europe (e.g. Price, 1987; MacDonald and Allen, 2001). Chalk can also act as both reservoirs and seals for hydrocarbons (e.g. Hardman, 1982; Mallon & Swarbrick, 2008). As such, the timing and origin of fracture-hosted permeability is an important constraint on understanding fluid-flow through C~~c~~halk.

The Frontal Fault zone structure at Selwicks Bay represents a significant damage zone associated with normal faulting in the region. This fault zone forms part of the FHFZ, but has much less offset than other fault-zones to the north (Bempton Fault) and south (Langtoft Fault) (Fig. 1a-1b). It is clear, however, that the large fissure systems forming the fault zone have acted as a major fluid conduit allowing voluminous fluid-flow through the chalk, possibly over a long time period of at least five million years. G~~Interestingly, g~~eochemical analyses of the calcite fills by Faÿ-Gomord et al. (2018) show that all the calcite veins share broadly the same chemical signature, which they link to an underlying source of meteoric fluids in the Triassic Sherwood Sandstone. ~~Although~~However, their ~~S~~salinity data~~ies~~ vary, suggesting some mixing with saline fluids. Given the development of open vugs and geopetal sediment fills with glauconite and microfossil fragments, we ~~posit~~propose that the fluid pathways were ~~a link to a~~ linked to a surface marine environment ~~is indicated~~ at the time of calcite mineralis~~z~~ation. The development of contemporaneous open fissures with sediment infilling due to wall rock collapse and washing ~~-~~in of finer materials from the surface, together with hydrothermal mineralis~~z~~ation sourced from below, and occurring ~~-~~during tectonic extension, is an increasingly recognised phenomenon in near surface fracture systems (< 1-2km depth; e.g. Wright et al., 2009; Walker et al., 2011; Holdsworth et al., 2019, 2020; Hardman et al., 2020).

We suggest ~~T~~that the~~e~~ fault has acted as a 'fluid superhighway' connecting deeper reservoir units (Triassic sandstones) with the surface during the ~~latest Cretaceous-earliest~~ Palaeocene to early Eocene. The existence of a fluid conduit of this kind potentially has major implications for storage and migration processes associated with reservoirs, whether they be for groundwater or hydrocarbons. Importantly, this structure is potentially of sub-seismic scale, indicating that even sub-seismic features may host large-scale fluid-flow, and produce significant conduits that exhibit high permeability over protracted time periods lasting millions of years. We should also point out that this is just one ~~small~~ fault of many in the FHFZ, and that many of the faults exposed inland are also associated with extensive veining, as well as secondary cementation of the C~~c~~halk adjacent to the faults. These secondary cements form hard chalk zones, which then potentially act as barriers to fluid-flow.

7.3 Implications for regional tectonics

The Flamborough Head Fault Zone forms a structural boundary that separates the Cleveland Basin to the north, and the Market Weighton Block to the south (Kirby & Swallow, 1987; Starmer, 1995). The history of the fault zone is thought to be influenced by the subsidence and later inversion of the Cleveland Basin, whilst the Market Weighton Block remained high and stable (Kent, 1980). The Flamborough Head Fault Zone is truncated to the east by several intersecting deformation zones (Central Fracture Zone, Dowsing Fault Zone, Sole Pit Basin; see Fig. 1), and truncated onland by the Humanby Trough-Peak Fault ~~zone~~ Zone (see Fig. 1 and Ford et al., 2020). The deformation that led to the formation and inversion of these basins has a long history extending from the Permo-Triassic to the Miocene (e.g. Starmer, 1995 and references therein), and the far-field stress associated with their formation may have some relevance to the Flamborough Head Fault Zone. The histories of these offshore regions are only constrained by seismic and borehole data, and correlation with known regional events. Therefore, dating of onshore structures such as those presented in the current study provides additional and new absolute timing constraints on the structural evolution at a regional scale.

There have been long-standing differences in the interpretations of the structural complexity of deformation in the Flamborough Head region. Some prefer a polyphase deformation sequence over a protracted time period from the later

Cretaceous to Neogene times (e.g. Starmer, 1995 and references therein) whilst others favour a somewhat simpler regime involving shorter-lived periods of strike-slip tectonics and polymodal or~~, possibly~~ polygonal extensional faulting (e.g. Peacock & Sanderson, 1994; Sagi et al., 2016, Faÿ-Gomord et al., 2017).

Our findings show that at Selwicks Bay, and by inference, along the FHFZ, a regionally significant extensional phase of deformation occurred over a protracted period during the ~~very latest Cretaceous~~ earliest Palaeocene to early Eocene times (ca. 64-55 Ma). Our field observations ~~We~~ suggest that this represents the youngest phase of deformation ~~seen~~ along the Frontal Fault zone – and by inference the FHFZ - post-dating any contractional or transpressional deformation. It should be noted that we cannot rule out that fluid-flow and tensile fracturing may have extended to even younger dates than our study implies. Interestingly, this timing of deformation overlaps with, but is broadly younger than the estimated late Cretaceous timing of widespread inversion and tectonic events across parts of NW Europe, discussed by Mortimore (2018).

The age ranges for calcite mineralis~~z~~ation are~~overlap~~ almost exactly coeval with the timing of igneous activity in W Scotland and Northern Ireland related to mantle upwelling ~~activity~~ forming the British Paleogene Igneous Province (Jolley & Bell, 2002), and associated regional uplift (Lewis, 2002; Nadin et al., 1997). In particular~~this regard~~, a clear ~~geological~~ temporal link exists ~~given the presence of~~between the calcite mineralis~~z~~ation and the intrusion of the nearby Cleveland Dyke, the easternmost exposure of which lies some 30 km NW of Selwicks Bay (Fig 1a). The intrusion of this dyke – which can be traced across a wide region of northern Britain, is thought to be ca. 58-55 Ma based on K-Ar dating (Fitch et al., 1978; Evans et al., 1973). Our findings therefore open up the intriguing possibility ~~that~~ that extension and associated fluid flow in the Flamborough Head region are related to the far field influence of N Atlantic opening processes.

Our findings further suggest that folding and thrusting of the C~~c~~halk at Flamborough Head must be older than ca. 64 Ma. Given the Santonian ~~to Campanian~~ age of the youngest C~~c~~halk affected by deformation (ca. 86-72 Ma; Whitham, 1993; Mortimore, 2020~~19~~), this implies that the inversion event can be no older than latest Cretaceous. In previous interpretations, much of the late stage compressional deformation along the FFHZ has been linked to inversion related to the far-field effects of the Alpine orogeny during the Neogene (Starmer, 1995). Clearly, our findings from Selwicks Bay cast significant doubt on this model. It seems possible that the earlier folding and thrusting seen at Selwicks Bay and elsewhere around Flamborough Head is related to a phase of strike-slip deformation along the FHFZ. Based on our findings to date, we cannot rule out the possibility that these strike-slip events overlap with the later extensional deformation, i.e. they are all manifestations of a protracted phase of regional transtensional tectonics in latest Cretaceous to Palaeocene times. Thickness changes in the C~~c~~halk around the faults exposed at Flamborough Head (see Mortimore, 2019 and references therein), are the only current evidence for extensional deformation occurring earlier than our oldest date of 64 Ma.

We propose that a careful reassessment of the deformation structures and sequences in the onshore and offshore regions around Flamborough H~~h~~ead is required, ideally with further absolute dating and palaeostress inversion analyses. More generally, our findings are a further illustration that the sequence, timing and tectonic significance of the Cenozoic history of the British Isles ~~may be~~is in need of significant~~ome~~ reassessment (e.g. see discussion in Parrish et al., 2018).

8 Conclusions

U-Pb dating of calcite vein-fill from Selwicks Bay provides constraints on the timing of faulting. Five dates, ranging from 63.9 to 54.9 Ma, indicate that formation of the mineralized collapse breccia within the extensional Frontal Fault zone occurred at ca. 63 Ma, with fluid-flow continuing to at least 55 Ma. Calcite from a Mode I tensile vein in the nearby wall rocks has a large age uncertainty but overlaps both these dates. A veinlet cross-cutting slickenfibres formed on a bedding parallel surface of a fold structure, places a lower boundary on folding at 56 Ma. The dates indicate that faulting within the Flamborough Head Fault Zone was Palaeocene in age. As an alternative to the polyphase ~~We dispute a~~ compressional and extensional model of Starmer (1995), we ~~(and tectonic inversion) origin for most structures at Selwicks Bay,~~ instead suggest~~ing~~ that, except for the possibility of syn-sedimentary slump structures (Mortimore, 2020), a more straightforward model involving overlapping strike~~-~~slip and extensional deformation may explain much if not all of the deformation at Selwicks Bay. Our study has shown that the extensional Frontal Fault zone at Selwicks Bay represents: [1] a fault-hosted fluid conduit that linked deeper sedimentary units to the shallow sub-surface, and hosted voluminous fluid-flow over a protracted time-scale; and [2] that its fault activity occurred within a 5-10 Ma time frame overlapping with that of the intrusion of the nearby Cleveland Dyke (ca. 58-55 Ma), the development of the N Atlantic Igneous Province and the regional uplift of NW Britain related to the opening of the North Atlantic.

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Code and data availability.

U–Pb data are presented in the Supplement Table, along with the corresponding methods and analytical details in the Supplement Text.

Supplement.

The supplement related to this article is available online at:

Author contributions.

NMWR and JKL collected the analytical data. NMWR, AF, JKL, CJ and REH conducted fieldwork and sample collection. NMWR, JKL and REH conducted sample imaging and petrography. All authors contributed to writing the paper.

Competing interests.

The authors declare that they have no conflict of interest.

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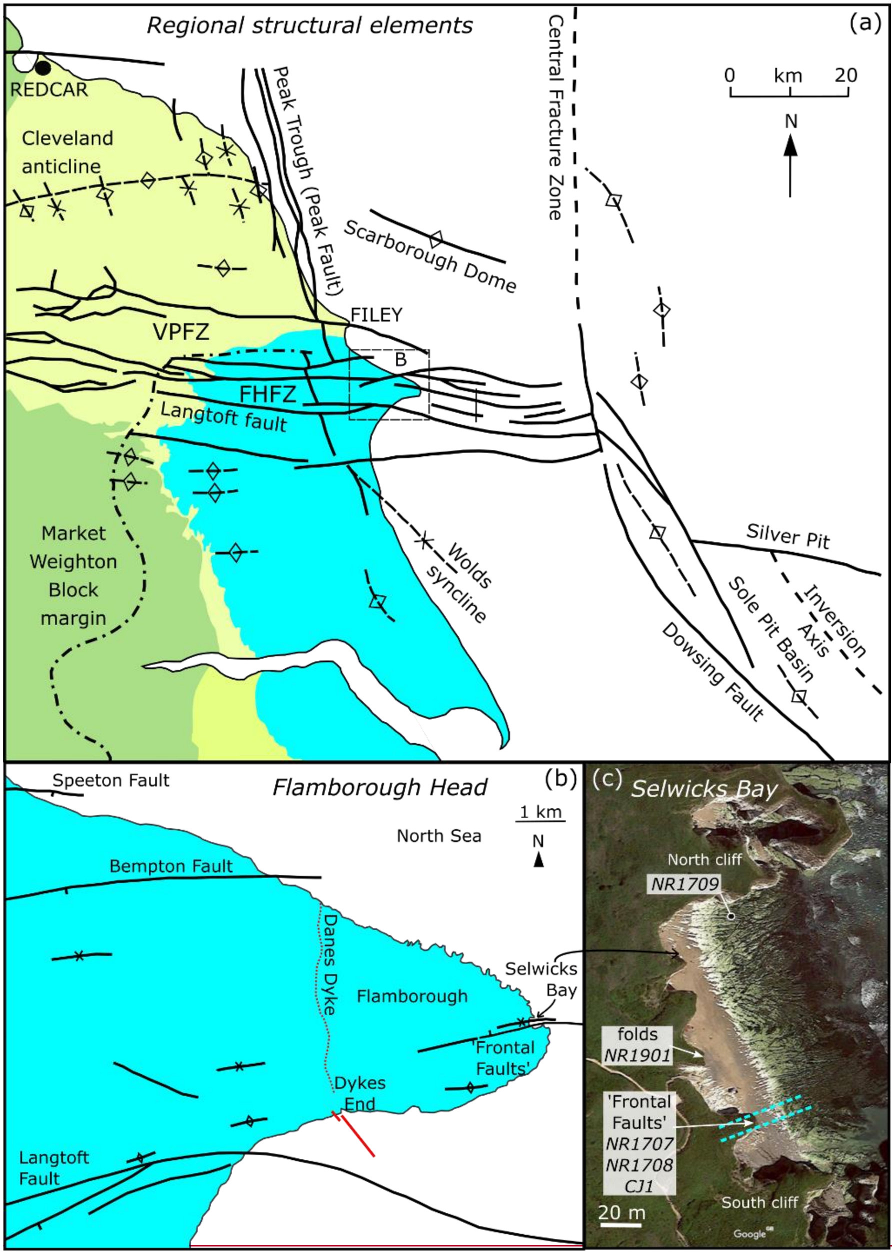

Regional structural elements
(a)
REDCAR
Cleveland anticline
Peak Trough (Peak Fault)
Central Fracture Zone
0 km 20
N
Scarborough Dome
FILEY
VPFZ
B
FHFZ
Langtoft fault
Market Weighton Block margin
Wolds syncline
Silver Pit
Inversion Axis
Sole Pit Basin
Dowsing Fault
Speeton Fault
Flamborough Head
(b)
1 km
North Sea
N
Bempton Fault
Danes Dyke
Flamborough
Selwicks Bay
'Frontal Faults'
Dykes End
Langtoft Fault
(c)
Selwicks Bay
North cliff
NR1709
folds
NR1901
'Frontal Faults'
NR1707
NR1708
CJ1
20 m
South cliff
Google

Figures

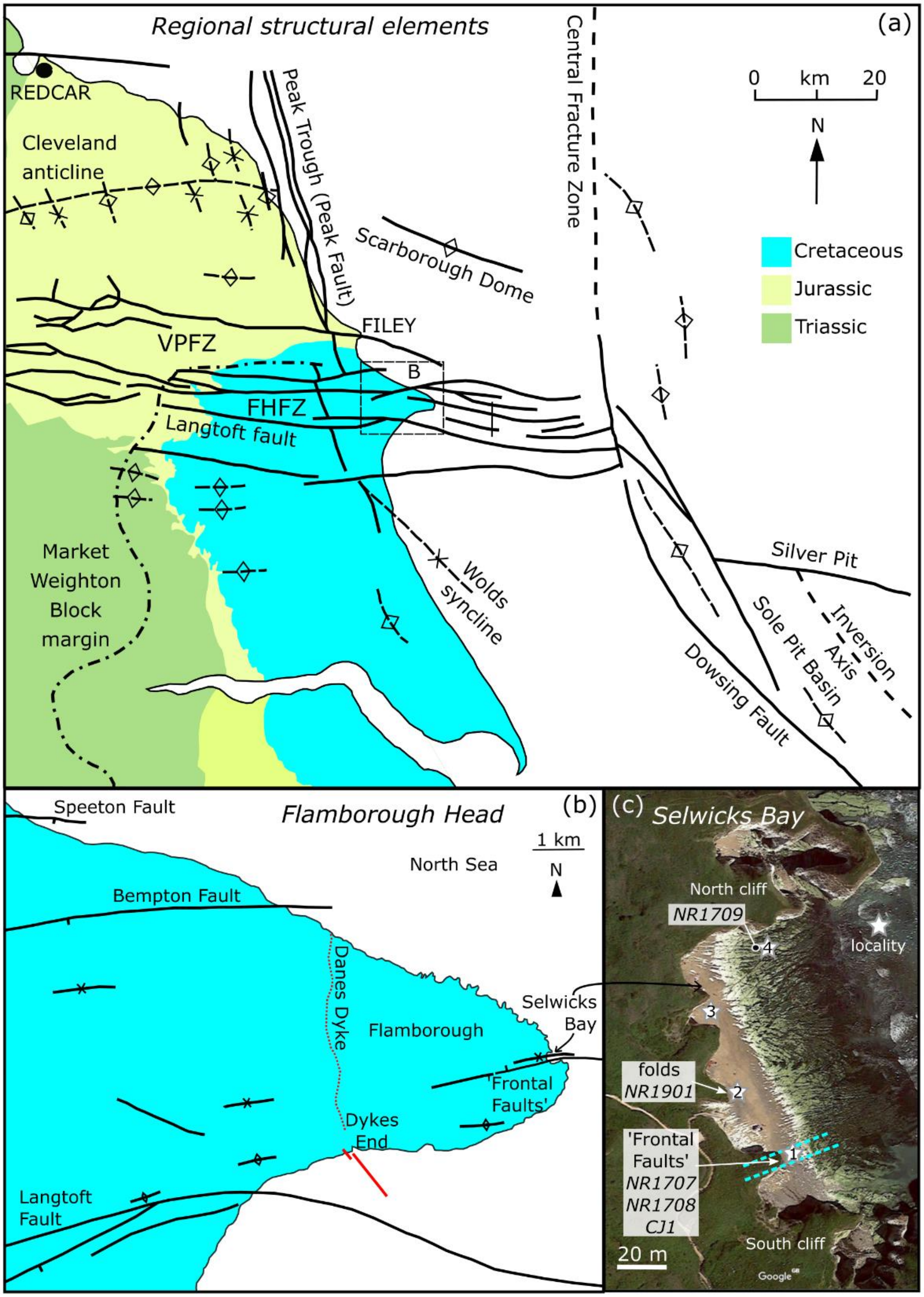

Regional structural elements
(a)
REDCAR
Cleveland anticline
Peak Trough (Peak Fault)
Central Fracture Zone
Scarborough Dome
0 km 20
N
Cretaceous
Jurassic
Triassic
FILEY
VPFZ
B
FHFZ
Langtoft fault
Market Weighton Block margin
Wolds syncline
Silver Pit
Inversion Axis
Sole Pit Basin
Dowsing Fault
Speeton Fault
Flamborough Head
(b)
1 km
North Sea
N
Bempton Fault
Danes Dyke
Flamborough
Selwicks Bay
'Frontal Faults'
Dykes End
Langtoft Fault
(c) Selwicks Bay
North cliff
NR1709
4
locality
3
folds
NR1901
2
'Frontal Faults'
NR1707
NR1708
CJ1
1
South cliff
20 m
Google

Figure 1. (a) Geological sketch map of the region around Flamborough Head, NE England, showing the regional structural elements. Modified after Powell (2010) and Starmer (1995), reproduced by permission of the Council of the Yorkshire Geological Society. (b) Geological sketch map of Flamborough Head showing main structural features. Modified after Starmer (2013), reproduced by permission of the Council of the Yorkshire Geological Society. (c) Satellite image of Selwicks Bay showing location of samples. Google map data: Imagery ©2020 CNES / Airbus, Getmapping plc, Infoterra Ltd & Bluesky, Maxar Technologies, Map data ©2020.

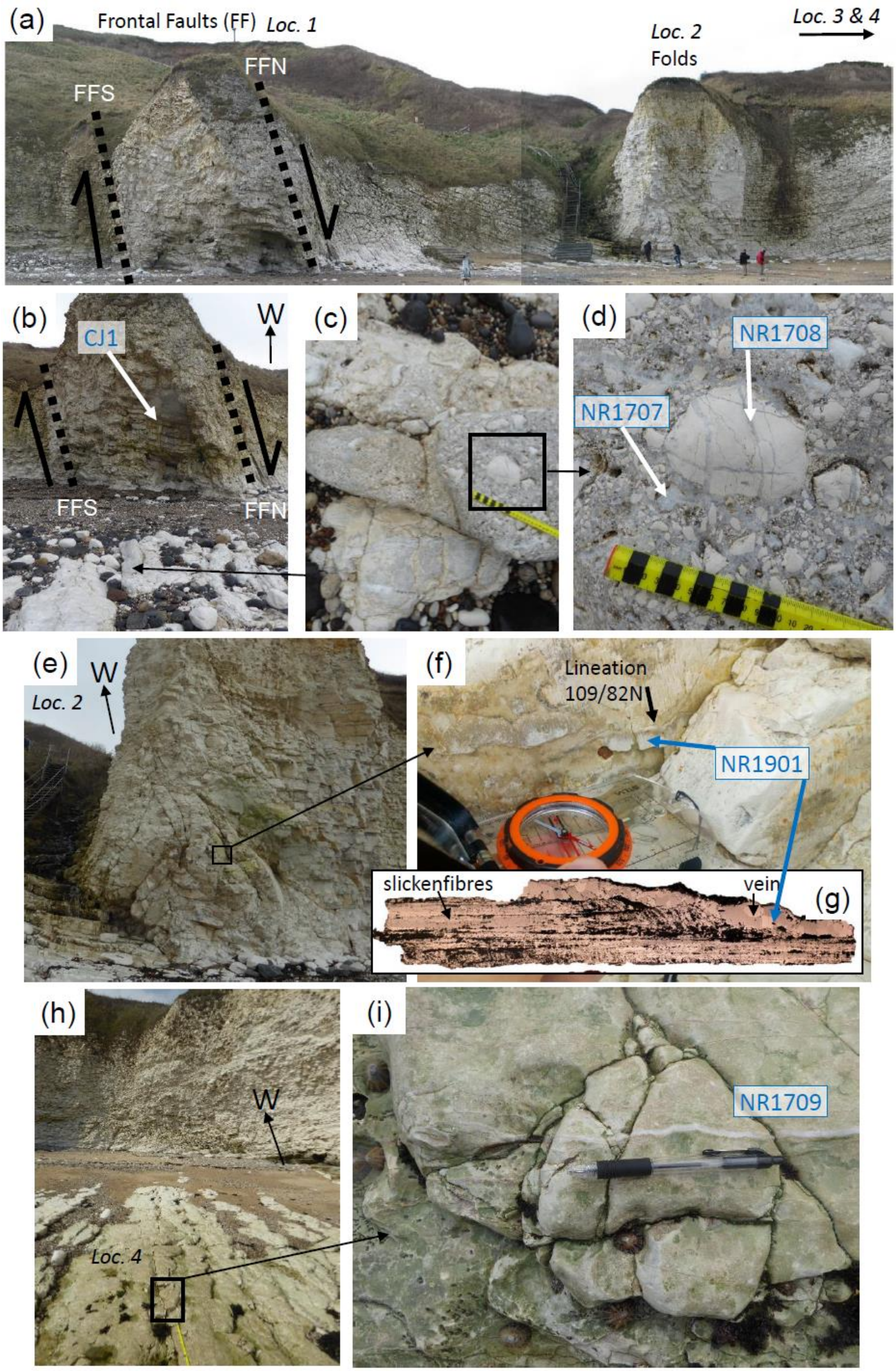
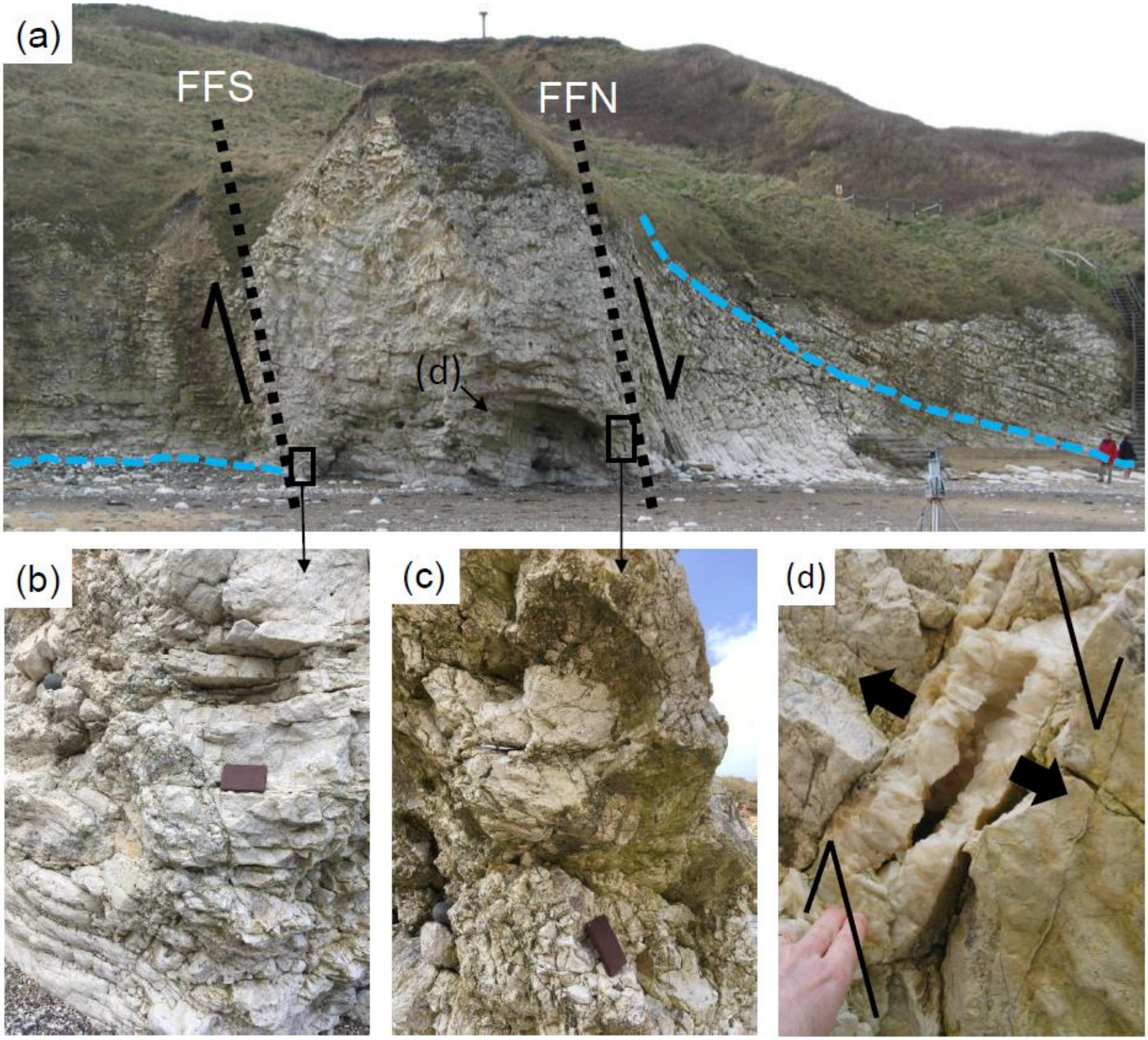

(a)
Frontal Faults (FF)
Loc. 1
FFS
FFN
Loc. 2
Folds
Loc. 3 & 4
(b)
CJ1
W
FFS
FFN
(c)
(d)
NR1708
NR1707
(e)
W
Loc. 2
(f)
Lineation
109/82N
NR1901
slickenfibres
vein
(g)
(h)
W
Loc. 4
(i)
NR1709

Figure 2. (a) View looking west of both the Frontal Faults (locality 1) and region of tight folding (locality 2). FFS = Frontal Fault South; FFN = Frontal Fault North. (b) Frontal Fault zone with location of samples NR1707 and NR1708 on foreshore. (c) Chaotic breccia fissure fill cemented by calcite with location of samples. (d) Close-up of clast with calcite vein (sample NR1708) and breccia cement (NR1707). (e) Locality 2 showing the location of sample NR1901 on the hinge of a fold. (f) Slickenfibres located on the bedding plane in the fold hinge. (g) Reflected light photograph of cross section view of slickenfibres and cross-cutting sparry vein; sample NR1901. (h) Locality 4 showing the foreshore pavement with sub-vertical E-W striking calcite filled veins. (i) Close-up of locality 4 and sample NR1709.


(a)
FFS
FFN
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(c)
(d)

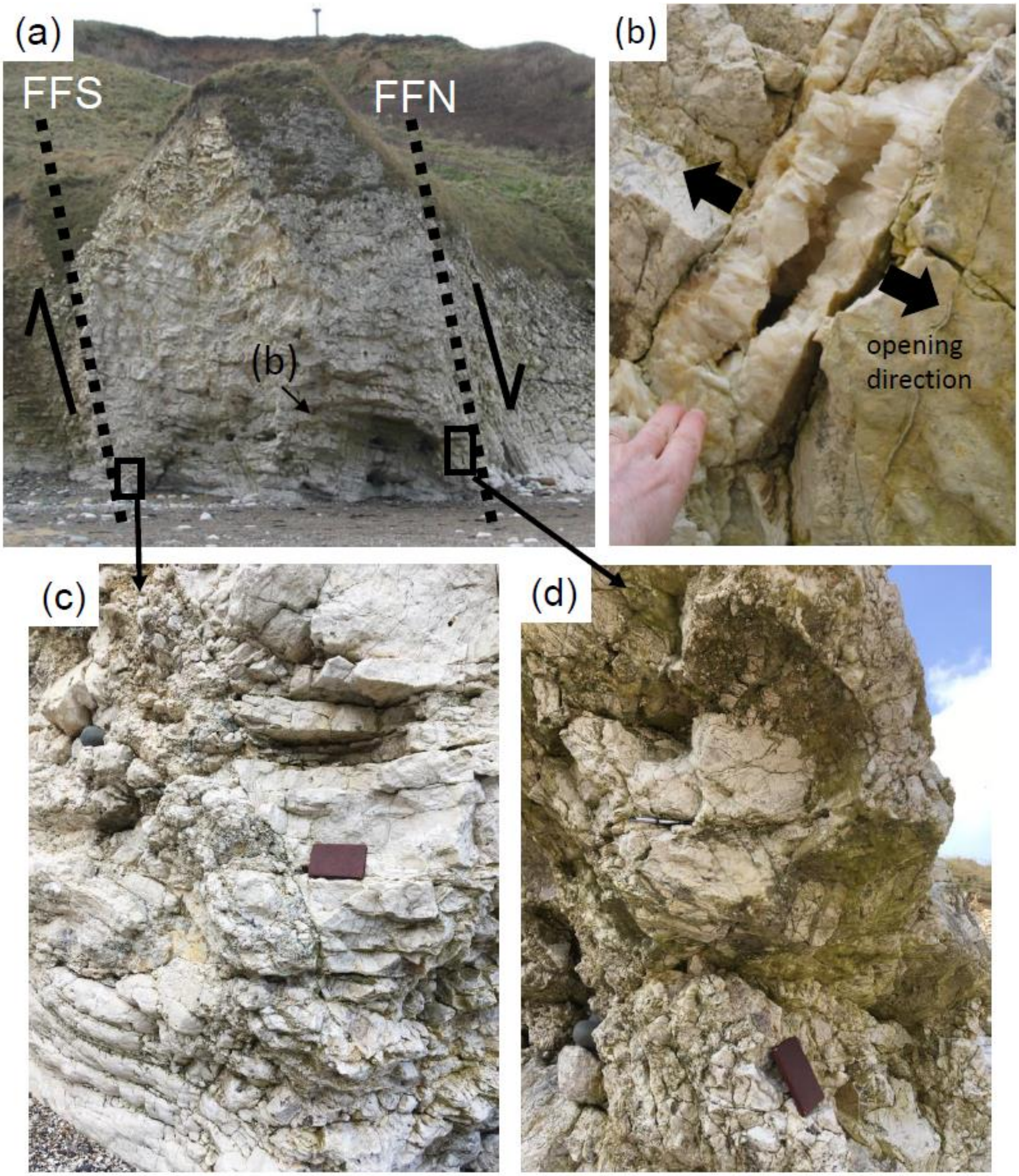
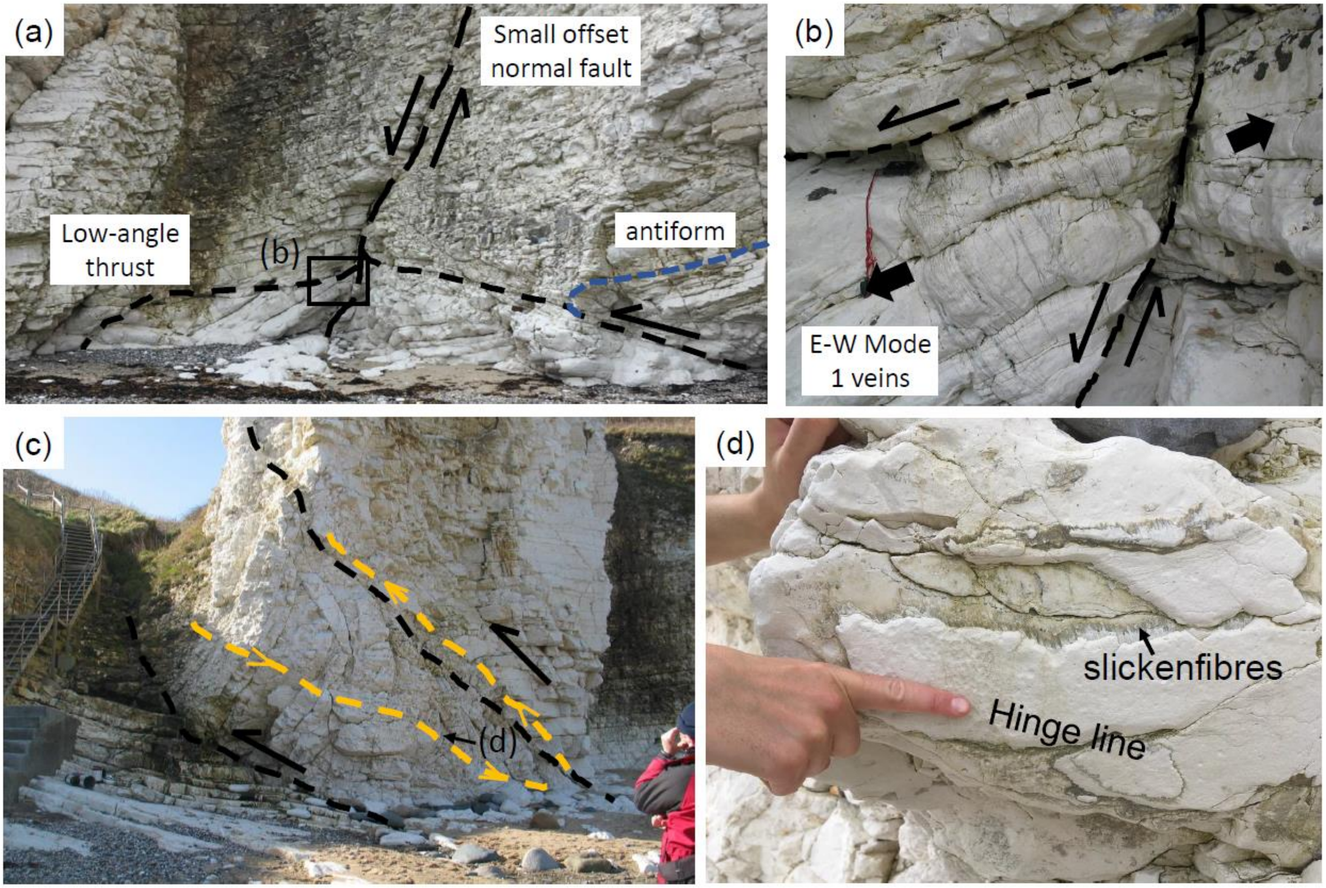


Figure 3~~2~~. (a) The Frontal Faults North and South (red dashed lines labelled FFN and FFS, respectively) viewed looking west in the cliffs at Selwicks Bay. ~~The blue dashed line indicates bedding in the chalk either side of the fault zone, showing a prominent zone of drag folding consistent with a north-side down sense of relative motion along the fault zone.~~ The locations of the images shown in b-d are ~~also~~ shown. (b) Open vuggy tensile vein with partial sparry calcite fill from brecciated region bounded by FFS and FFN. Note the opposite dip to the bounding faults consistent with N-side down motion. (c) Relatively planar fault zone with breccia that forms part of the FFS. Note gentle drag folding in both hangingwall and footwall consistent with N-side down motion. (d~~e~~) Wider, more irregular fault breccia that forms part of the FFN, with clasts of wall rocks up to 1.5m across.



~~(d) Open vuggy tensile vein with partial sparry calcite fill from brecciated region bounded by FFS and FFN. Note the opposite dip to the bounding faults consistent with N-side down motion.~~

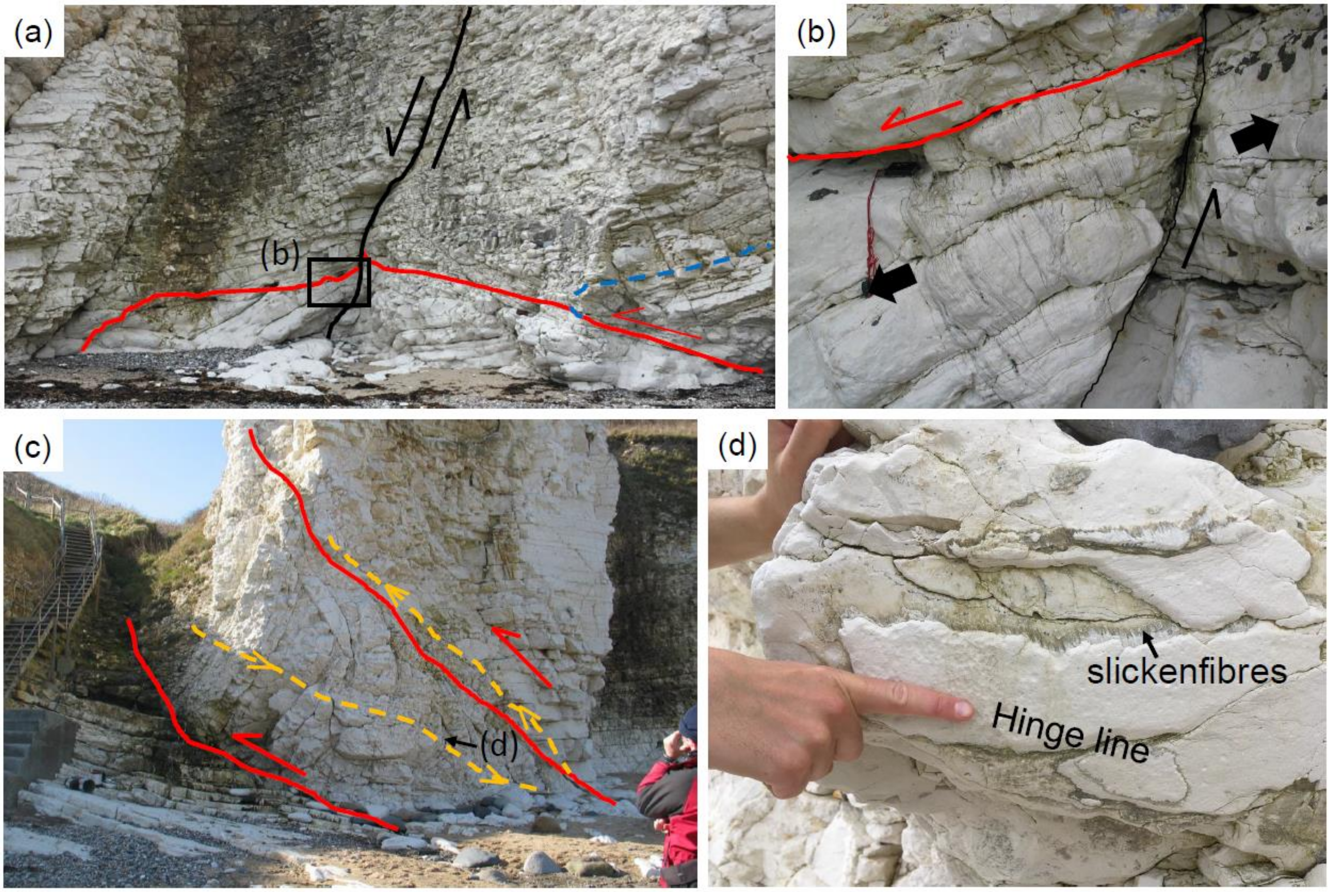
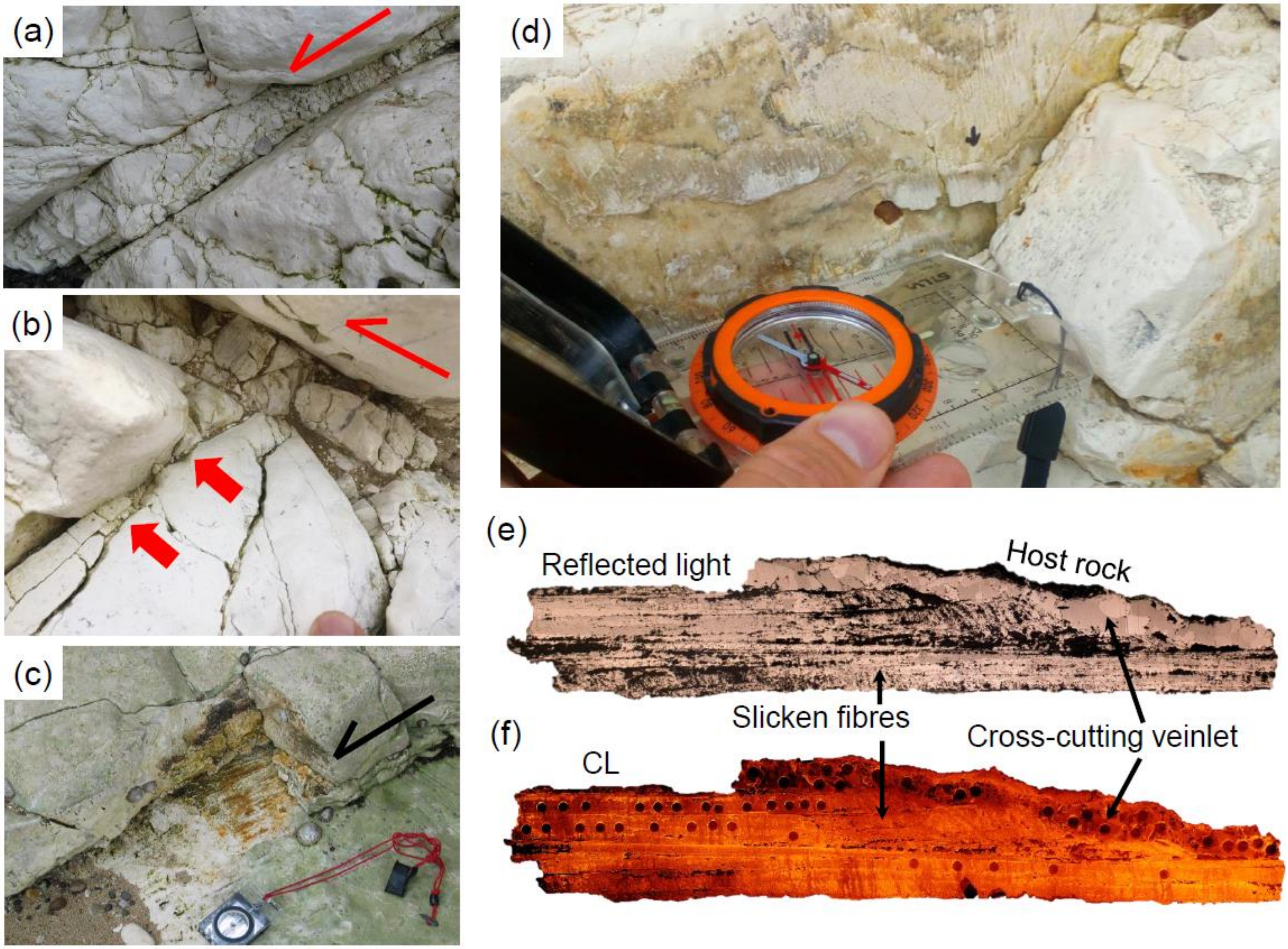


Figure ~~3~~4. (a) Locality 3 - View looking W of top-to-the-S thrust fault ~~(red)~~ cross-cut by S-side-down, steeply dipping normal fault ~~(black)~~, north side of Selwicks Bay. Bedding in the hangingwall (blue) of the thrust is deformed by a cm-scale, S-overturning anticline. Box shows location of (b). (b) Close up view of normal fault shown in (a) with N-dipping tensile veins filled with calcite in hangingwall consistent with S-side-down sense of throw. (c) Locality 2 - View looking W of metre-scale, close to tight, southward verging antiform-synform pair (fold axes in yellow) and associated top-to-the-S low to moderately N dipping thrust faults (black dashed lines) some 40 m north of the FFN. (d) View looking S of exposed synformal fold hinge shown in (c) with bedding-parallel calcite slickenfibres oriented oblique to the fold hinge.


(a)
(b)
(c)
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(e)
Reflected light
Host rock
Slicken fibres
(f)
Cross-cutting veinlet
CL

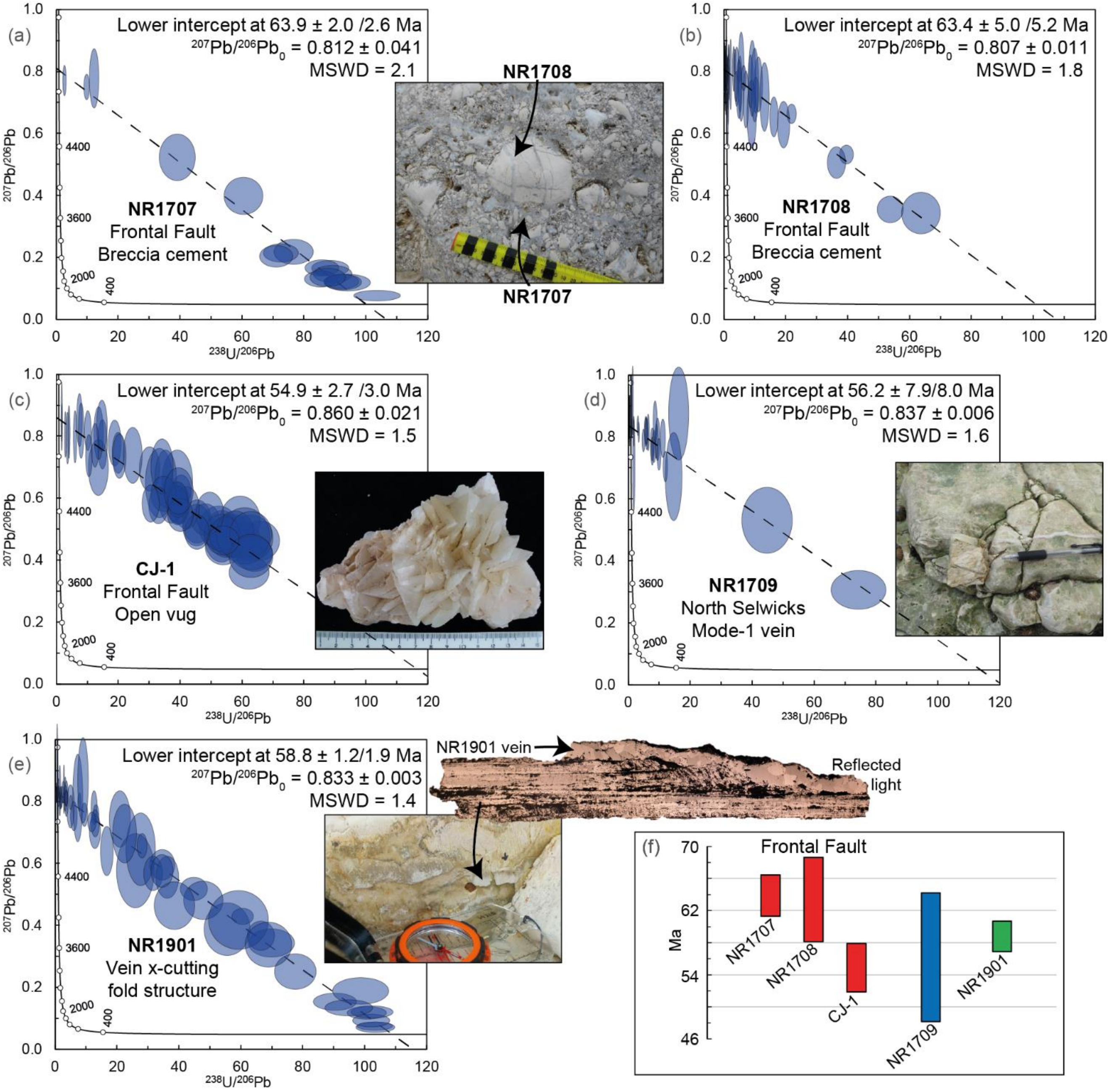
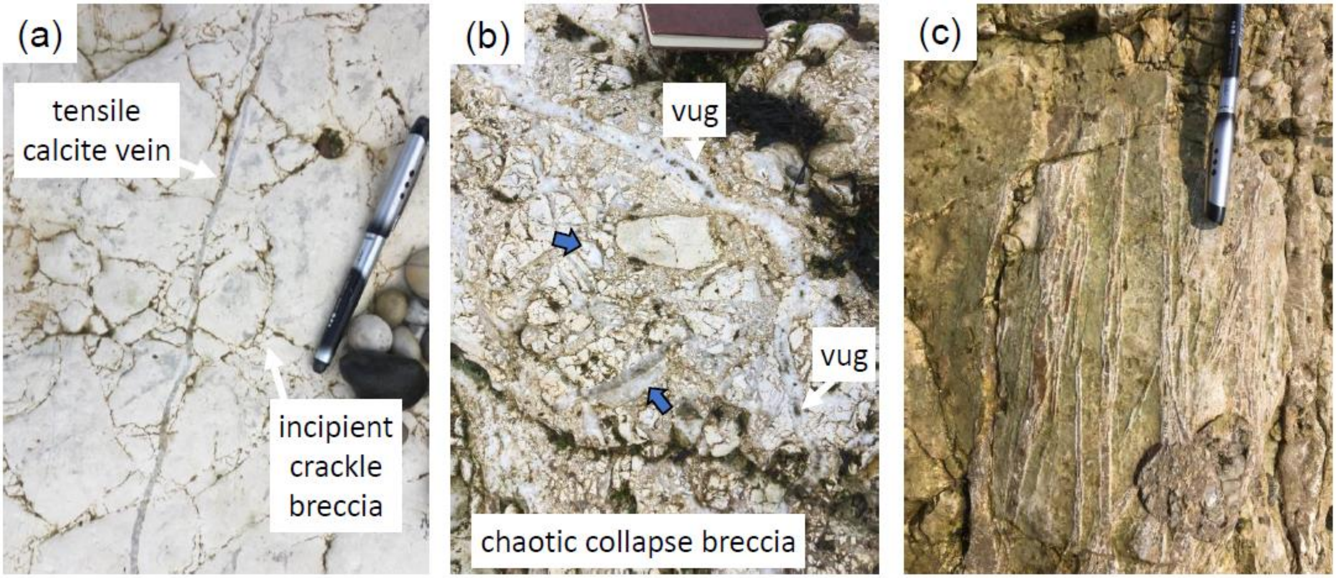


Figure 5. (a-e) Tera-Wasserburg plots of U-Pb results (all uncertainties shown and quoted at 2σ), and corresponding sample images (see Supplementary Text for full size images). (f) Comparison of the five dates plotted with their 2σ uncertainties.

Figure 6~~4~~. Structures associated with contractional structures in Selwicks Bay; all from locality 3. (a) Crush breccia along top-to-the-S thrust fault reoriented by later, normal fault-related tilting. (b) Crush breccia and brown gouge derived from chalk and shale, respectively, associated with top-to-the-S thrust fault with narrow gouge injections into footwall, one of which is arrowed.

(c) Calcite-hematite slickenlines associated with top-to-the-S thrust fault.

~~(d) Close-up of stepped, bedding parallel calcite slickenfibres from synform hinge (see Fig 2d). (e) Reflected light and (f) cathodoluminescence (CL) images of bedding-parallel slickenfibres (within polished block) and later, cross cutting blocky calcite veinlet. Note that the CL image shows the craters made by the laser during analysis.~~



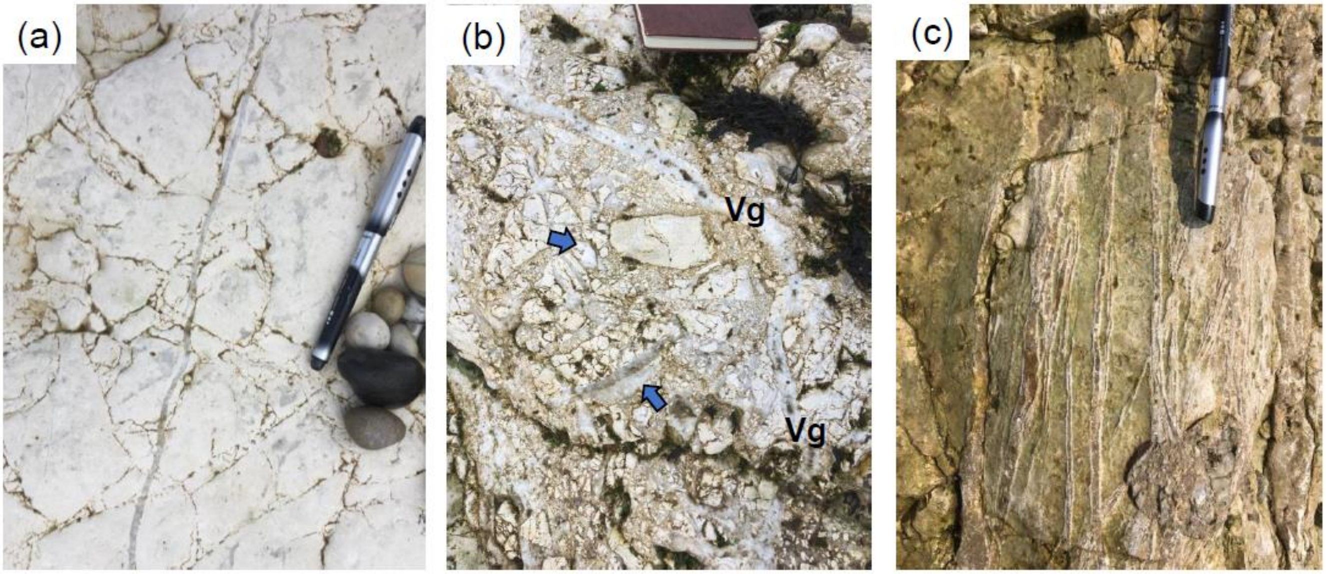
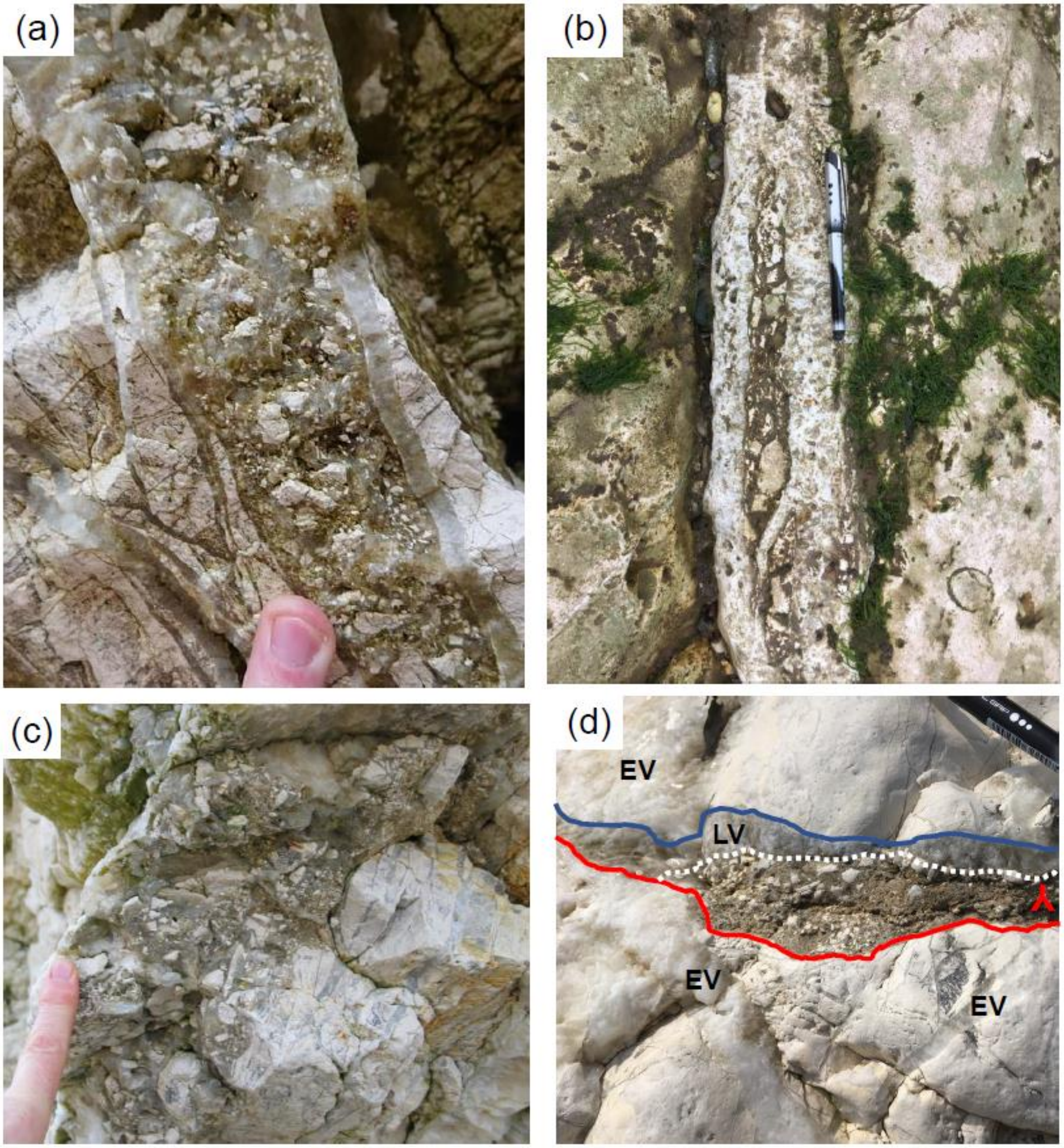


Figure 7~~5~~. Breccia development associated with extensional movements along the Frontal Faults zone in Selwicks Bay in the region bounded by the FFS and FFN; all photos are from the foreshore.~~.~~ (a) Incipient crackle breccia development (plan view)~~viewed in plan~~ looking at a bedding plane in chalk that is cross-cut by a narrow calcite-filled tensile vein. (b) Cross-section view of typical chaotic collapse breccia with little evidence for shearing or attrition of clasts. Note that calcite veins occur in clasts (examples arrowed) and as cross-cutting later vuggy features (labelled vug~~Vg~~). (c) Composite calcite veins in plan view from foreshore below high tide with younger orange-stained ferroan calcite and older white non-ferroan calcite rims.


(a)
(b)
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(d)
EV
LV
EV
EV

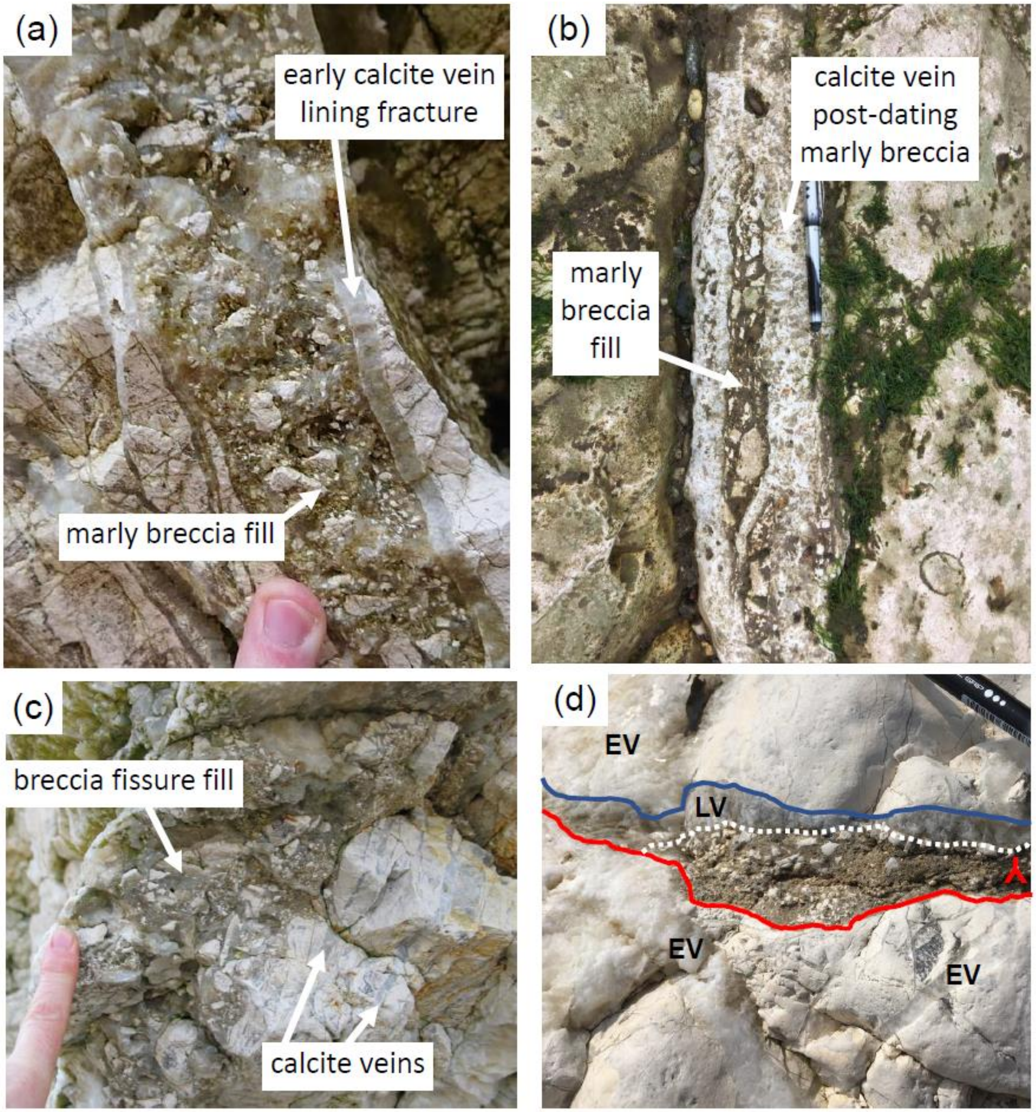
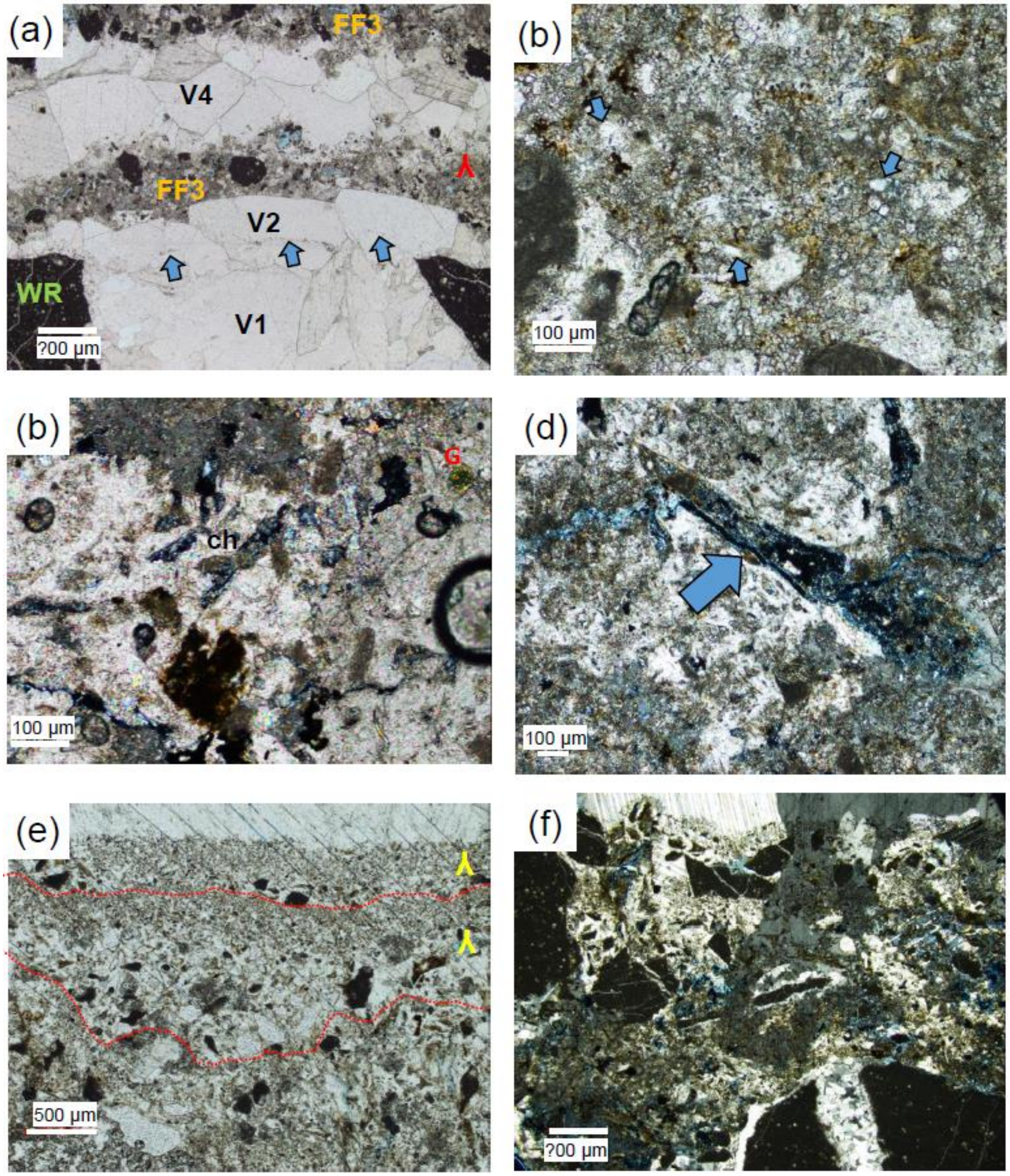


Figure 8~~6~~. Brown-coloured marly breccias and sediment fills in tensile fissures associated with the Frontal Fault zone, Selwicks Bay; photos a and c from the cliff, and b and d from the adjacent foreshore.~~.~~ (a) Marly breccia fill in cross-section view that post-dates sub-parallel calcite veins that line fracture. (b) Marly breccia that pre-dates calcite cemented breccia in plan view. (c) Steeply inclined fissure fill in cross section view that obliquely cross-cuts adjacent calcite veins. (d) Oblique view of irregular subhorizontal zone of fine marly sediment filling the lower part of a fracture that cross-cuts an earlier calcite vein (EV), whilst the upper part of the cavity is filled by a later calcite vein (LV). The sediment is crudely bedded and forms a geopetal fill that youngs upwards, as indicated by the inverted Y symbol.


(a)
FF3
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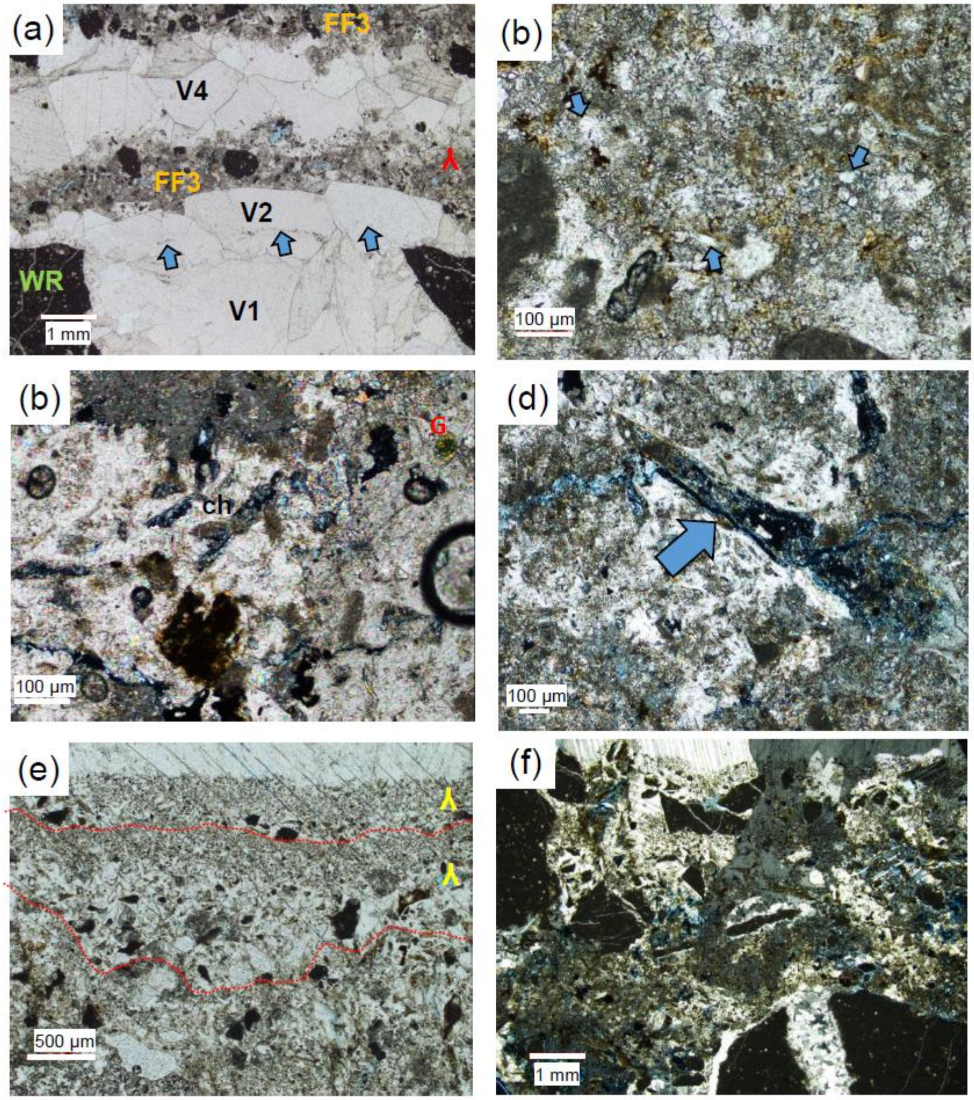
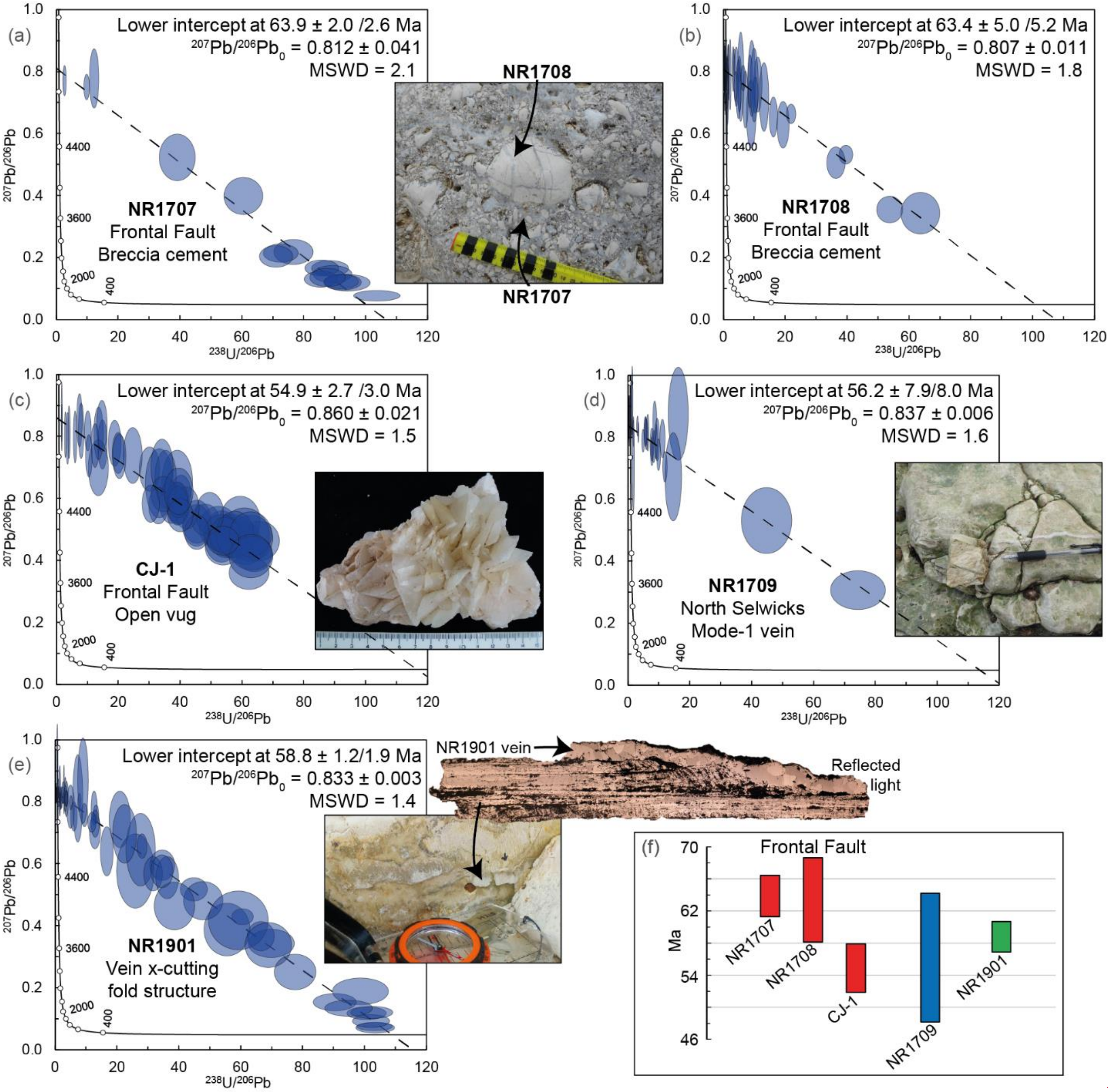


Figure 9~~7~~. Thin sections of sediment fills from Selwicks Bay Frontal Fault zone taken in plane polarised light unless indicated otherwise. (a) Chalk wall rocks (WR) and earlier calcite vein fills (V1, V2) unconformably overlain by sediment fill (FF3) cut by slightly later vein (V4); note that the mineral cement in the graded sediment grows in optical continuity with the V4 vein. Note also the line of inclusions separating V1 and V2. (b) Details of calcite-cemented sediment fill showing dark wall-rock clasts, hematite staining, clastic qtz grains (arrowed) and pale sub-angular clasts of earlier calcite. (c-d) As (b), showing included clasts of chert (ch) and glauconite (g) and sponge spicule (arrowed). (e-f) Cockade-style cementation of graded or complex sediment fills where the calcite cements are in optical continuity with the overlying vein fills. (f) is taken with crossed polars.



~~Figure 8. (a-e) Tera-Wasserburg plots of U-Pb results (all uncertainties shown and quoted at 2σ), and corresponding sample images (see Supplementary Text for full size images). (f) Comparison of the five dates plotted with their 2σ uncertainties.~~