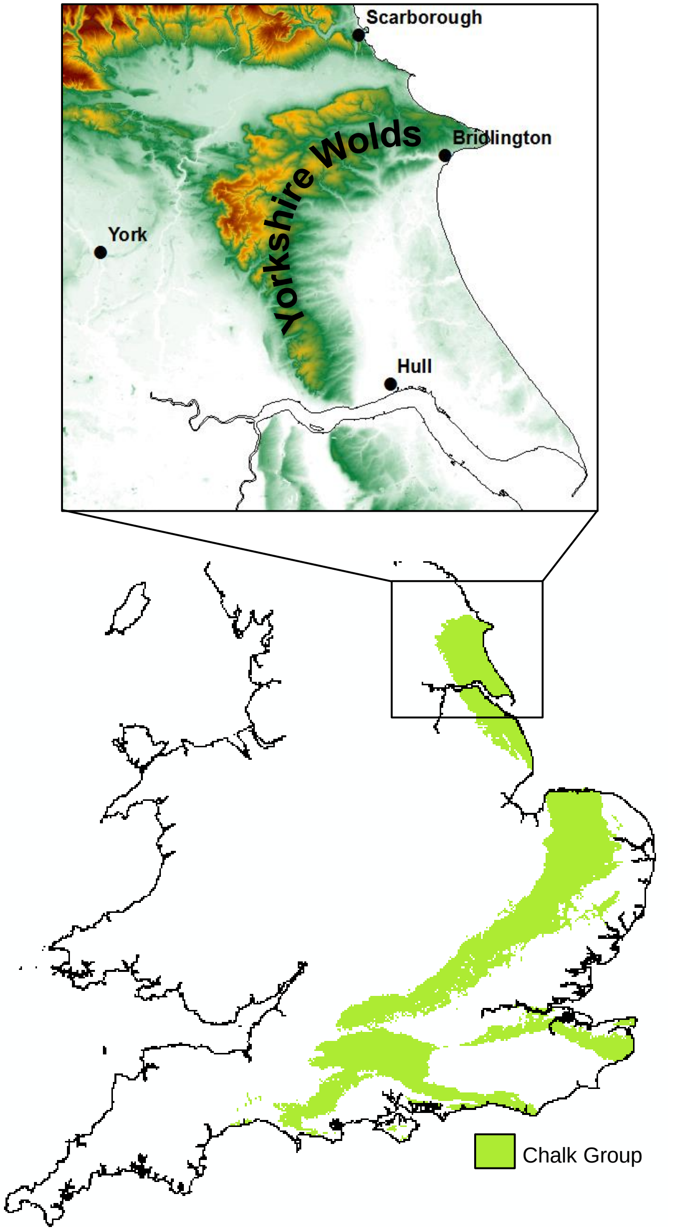
# Surface and subsurface fault mapping in the Yorkshire Wolds, UK.

*Vernon, R., Ford, J., Watkinson, K., Haslam, R., Woods, M., Farrant, A., Burke, H., Davis, A., Lear, J., Tarnanas, H. & Wrathmell, E.*

# Background

- The Upper Cretaceous Chalk Group crops out across a significant area of southern and eastern England and extends offshore into the North Sea.
- The Chalk is an important source of groundwater across England, however the different properties of the Chalk Group Formations and the effects of dissolution, karstification and faulting on groundwater flow are little understood.
- In this project we have used a multidisciplinary approach to map a fault network from the North Sea which intersects one of the UK's major aquifers and determine the importance of the fault network for groundwater flow within the region.

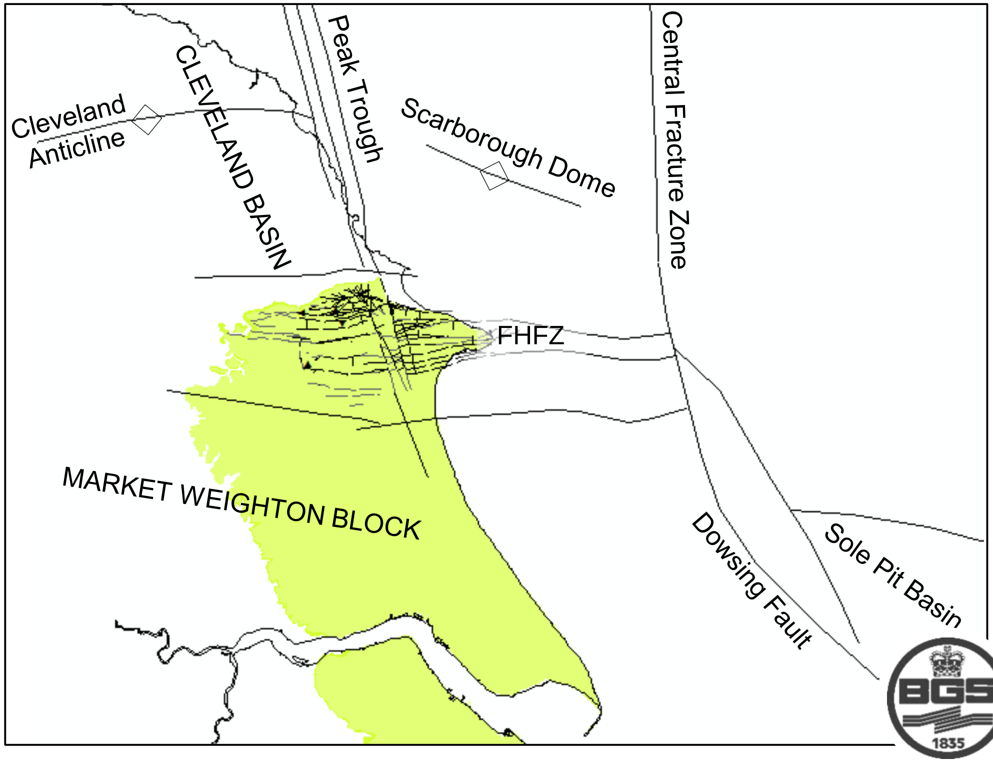
- The Yorkshire Wolds is a region of low hills located east of York, between Scarborough and Hull, in northeast England, which is underlain by bedrock of the Chalk Group and are transected by two major fault zones.
- The Chalk of the Yorkshire Wolds is a principal aquifer and the main source of water supply in East Yorkshire. The aquifer and associated groundwater system is directly influenced by the properties and distribution of the Chalk formations, faulting and superficial deposits that locally conceal the Chalk.
- Current geological datasets for the region are based on historical mapping and do not reflect modern geological understanding, or consider more recent surface and subsurface data.
- To rectify this a collaborative geological study between BGS and the Environment Agency has integrated a wide range of surface and subsurface data, literature and direct field evidence to create a revised geological interpretation for the northeastern Yorkshire Wolds, including the first detailed structural interpretation of several regionally important fault zones that cut the aquifer.




DEM from NEXTMap Britain elevation data from Intermap Technologies ©NEXTMap®. Map contains Ordnance Survey Data ©Crown Copyright and database right 2013. Geological data British Geological Survey © UKRI 2020.

# The Flamborough Head Fault Zone

- The Flamborough Head Fault Zone (FHFZ) is a regionally significant, E-W tending fault zone which cuts the Chalk Group Group in the northern Yorkshire Wolds. It marks the southern extent of the Cleveland Basin and the northern margin of the Market Weighton Block, a structural high which affected sedimentation during the Jurassic and Cretaceous.
- Offshore, to the east, the FHFZ merges into the NNW-SSE trending Dowsing Fault zone, a long-lived fault structure which formed in the Late Palaeozoic and has been successively reactivated (Van Hoorn, 1987).
- The FHFZ is related to an old (Mid-Late-Devonian Acadian Orogeny) deep structure that has been reactivated a number of times. During the Permian-Triassic and the late Jurassic-early Cretaceous it was reactivated as a series on E-W trending normal faults. These faults were then reactivated as reverse faults to accommodate late Cretaceous-early Cenozoic inversion of the Cleveland Basin, which caused over 1.8 km of uplift across the region (Sagi et al., 2016).
- The FHFZ is dissected by a N-S trending graben, the Hunmanby Trough (HT), which forms the onshore extension of the Peak Trough Fault System (PTFS). The PTFS formed in the late Triassic-early Jurassic as a graben due to regional E-W extension. It was reactivated during the late Cretaceous-early Cenozoic inversion due to transpression and offsets major E-W trending faults within the FHFZ (Hibsch et al., 1995; Sagi et al., 2016).
- The FHFZ is well exposed and described from coastal sections at Flamborough Head. However, inland poorly exposed due to extensive drift cover. In this study we have used a combination of field mapping, borehole interpretation, remote sensing, 2D seismic interpretation and passive seismic to understand the FHFZ and how it affects groundwater flow within the aquifer.

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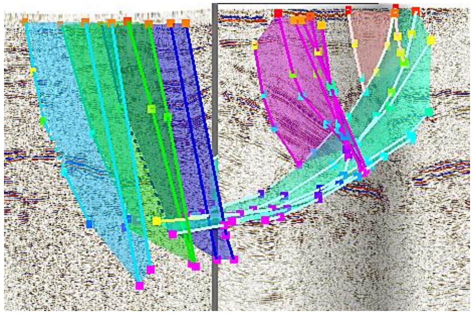
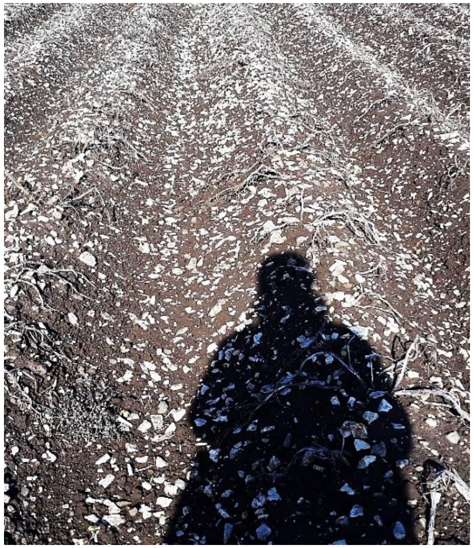
# Fault Mapping Methods

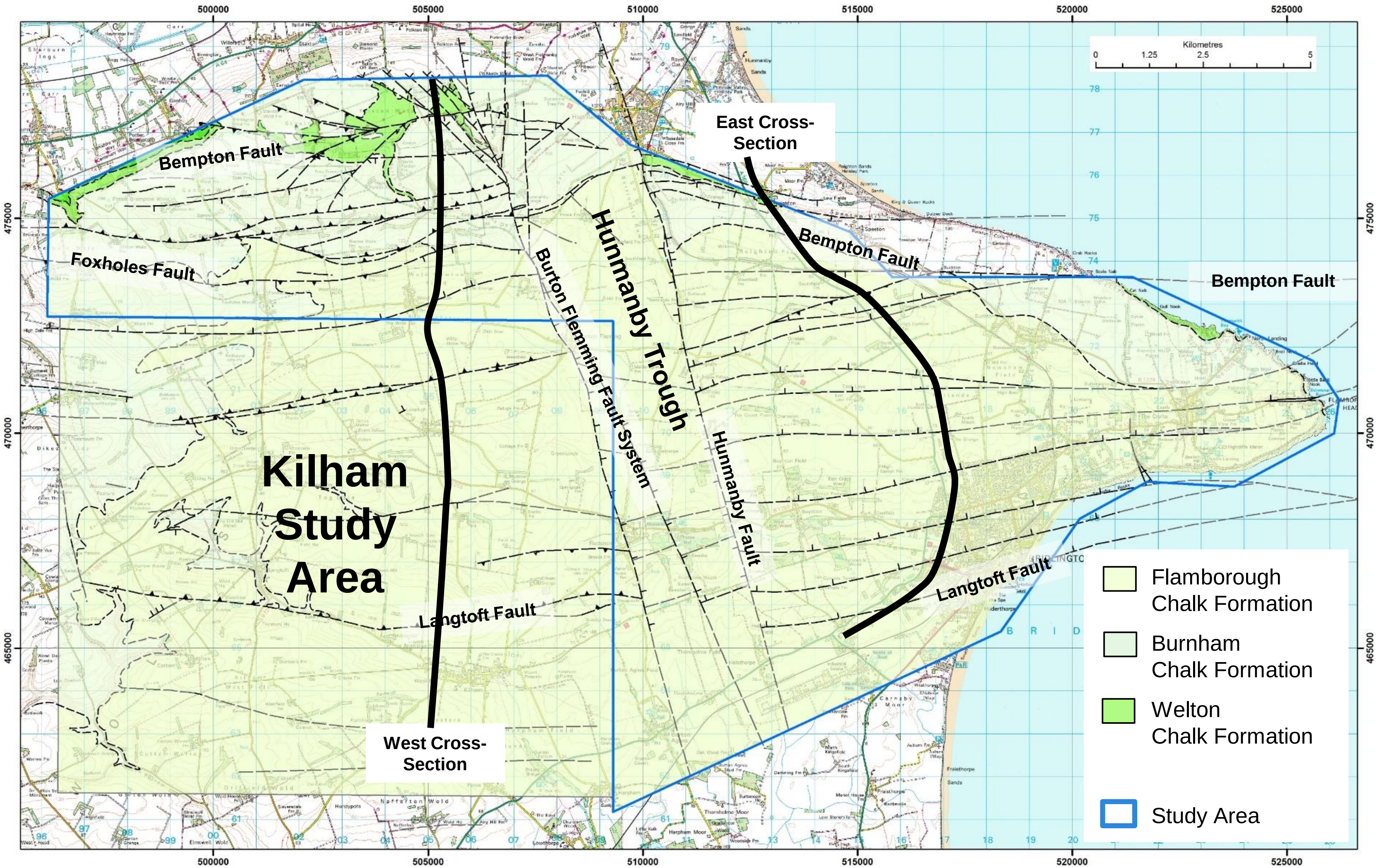





Calcite veining and exceptionally hard chalk is associated with the majority of faults in the area. Veined and hard chalk can be found in outcrop and brash. The veining varies in intensity and size from sparse sub-mm calcite veinlets to cm-scale veins that comprise > 30% of the rock mass. The veining and recrystallization of the chalk is thought to be related to fluid flow within fault zones. Cross-cutting relationships indicate multiple phases of mineralisation.

- *Remote Sensing* – The mineralised and recrystallized nature of the faults leads to subtle ground features, such as raised ridges and lineaments, crop growth patterns, brash intensity variations, which can be picked out by analysing DEMs and aerial photographs.
- *Field Mapping* – Field surveying was completed by a team of 6 geologists. Fieldwork was timed to coincide with optimal conditions – low crop-height and good daylight – to allow effective observations of soils, 'brash' (loose rock material entrained in the soil) and landforms. Data was collected from traverses, visits to pits and coastal sections.
- *Palaeontology* – The Chalk succession is associated with fossil assemblages that can be used to identify distinct biostratigraphical zones which can be correlated with lithostratigraphical units and can help infer formation boundaries and fault geometries.
- *Passive Seismic (Tromino)* – Results from previous Tromino passive seismic surveys in the neighbouring Kilham area and on Flamborough Head were available to assist with fault identification in the shallow sub-surface.
- *Borehole Interpretation* – Borehole logs which ranged in depth up to 250m were used to establish base chalk depth across the region and to help identify key horizons within the chalk where possible. This highlighted step-changes in the depth of the chalk base likely caused by faulting.
- *Seismic Interpretation* – 250 line-kilometres of 2D onshore seismic data was available within the area and was interpreted using Petrel. The data was acquired to understand the deeper structure of the fault zones to establish a consistent regional structural framework and context for the deformation of the chalk aquifer.

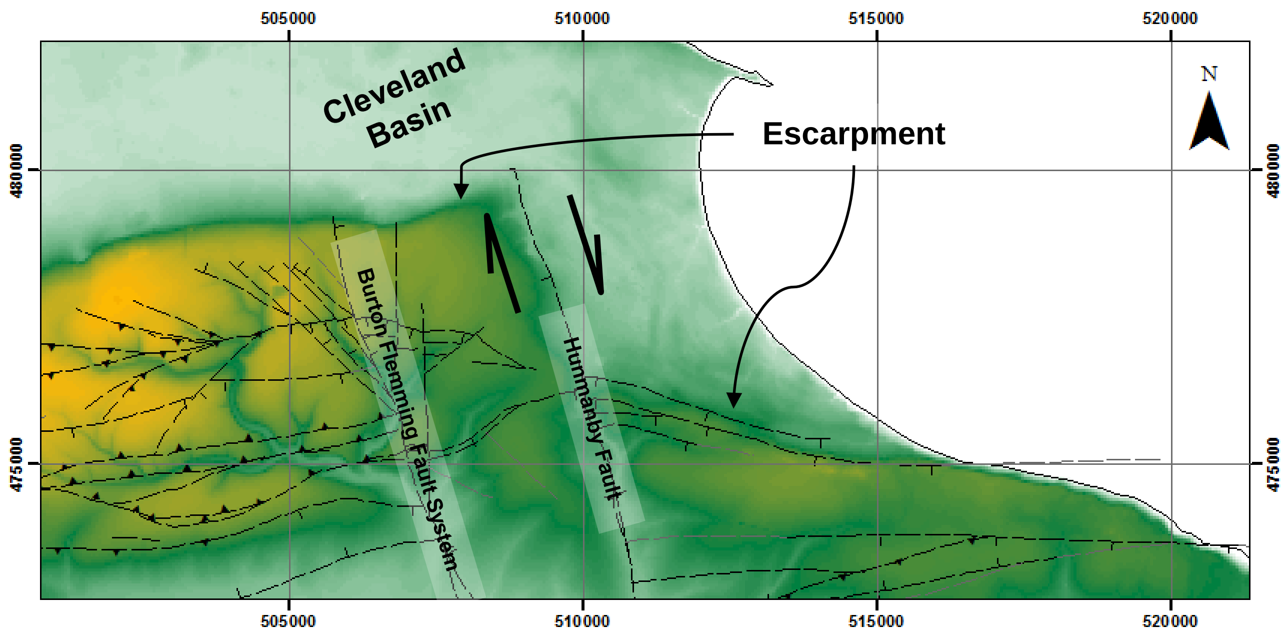
# North Yorkshire Wolds Fault Map




Map showing the revised bedrock geology, fault traces and cross-section locations for the study area, incorporating parts of the Kilham Study from Farrant et al. (2015). Contains Ordnance Data © Crown Copyright and database rights 2020. Ordnance Survey Licence no. 100021290. Geological data British Geological Survey © UKRI 2020.

# North Yorkshire Wolds Fault Map - 1

- The revised fault map (previous slide) clearly shows a number of E-W faults which are dissected by three main N-S trending faults. This map is a compilation of the remote sensing, seismic, field, palaeontological and borehole studies. Only the area inside the blue line was considered in this study, subsequent studies over the coming years expect to expand this map over the whole Yorkshire Wolds. The main faults have been labelled on the map.
- The normal faults which bound the Hunmanby Trough clearly offset both the Langtoft and Bempton Faults dextrally, suggesting they also have a strike-slip component. This can be seen expressed in the topography at the northern edge of the study where an escarpment, sloping northwards into the Cleveland Basin, has a step along the Hunmanby Fault. A similar step is not apparent in the escarpment along the Burton Flemming Fault System (BFFS) and a network of splaying faults in the northwest of study area, suggests the BFFS terminates at the north of the field area with the fault splays distributing the strain. In the south of the study area the BFFS is composed of two strands, with the seismic data suggesting that the western-most of these accommodates most of the normal displacement.




- Tracing individual faults through the Hunmanby Trough has been challenging; both the Hunmanby Fault and the BFFS have wide zones of calcite veining and recrystallisation, there is very little seismic data in this region and access to the land has not always been possible.

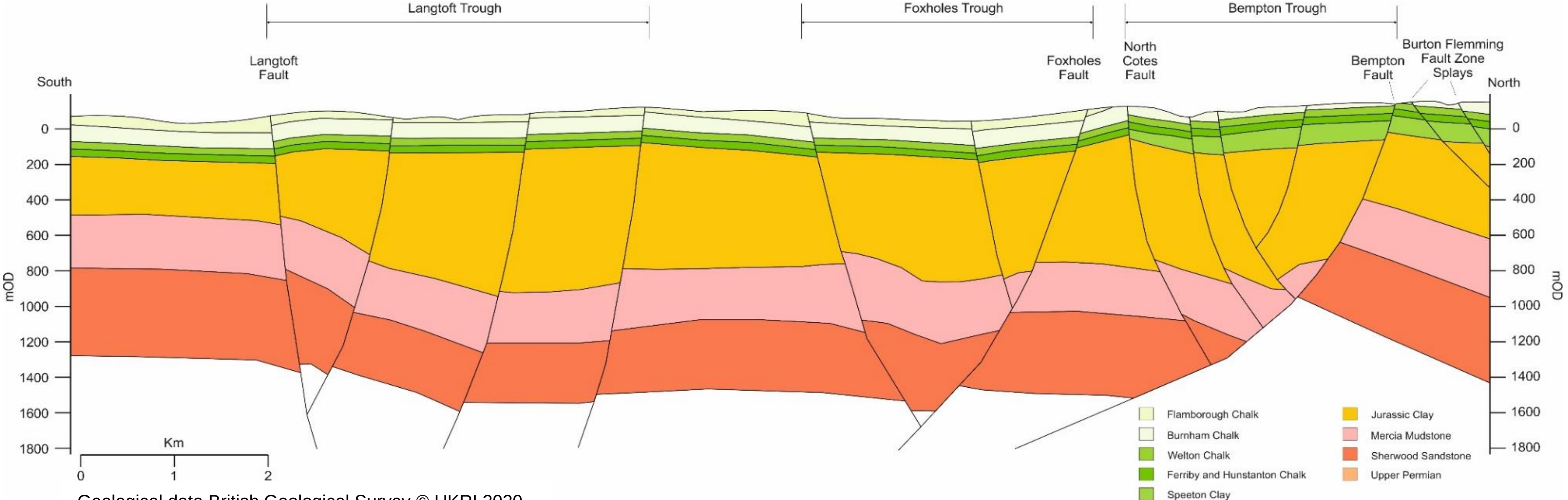
# North Yorkshire Wolds Fault Map - 2

- In the northwest part of the study area the E-W faults are inferred from remote and field-based evidence. Several faults are associated with bright anomalies in aerial photography and coincident ridges in DEM data, which can be up to 160 m wide and traced for 2 – 3 km. These zones are associated with tectonically brecciated chalk, calcite cementation, veining and recrystallised chalk. Both normal and reverse faults are inferred at the surface from lithostratigraphic offsets, seismic interpretation, borehole logs and biostratigraphic evidence. On some faults offset interpretations contrast, some faults which have evidence for normal offsets at depth display evidence of reverse offsets at the surface. This suggests many of the faults have a complex history of growth and reactivation.
- East of the Hunmanby Trough the FHFZ is also characterised by E-W trending faults, although the Langtoft Fault, in the south, trends WSW-ENE, causing the width of the FHFZ to decrease eastwards. North of the Langtoft Fault, a number of faults trend parallel – sub-parallel with the Langtoft Fault and all appear, based on seismic interpretation, to have normal offsets. Many of the faults in this area are characterised by relatively sparse calcite veining and recrystallization, making surface mapping of the faults difficult. Much of this area is covered by till meaning seismic interpretation has been relied on to identify some faults, therefore any sub-seismic may have been missed. In the central-northern part there is a paucity of seismic lines thus the deeper structure of some of the faults is unclear. Limited borehole and biostratigraphical evidence suggests that some of these faults may have reverse offsets in the near-surface, also implying a complex reactivation history.


Aerial photographs with arrows pointing to lineaments in the landscape. Aerial Photography © UK Perspectives.

Calcite veining and brecciation in the Flamborough Chalk at Flamborough Head.

# Western FHFZ

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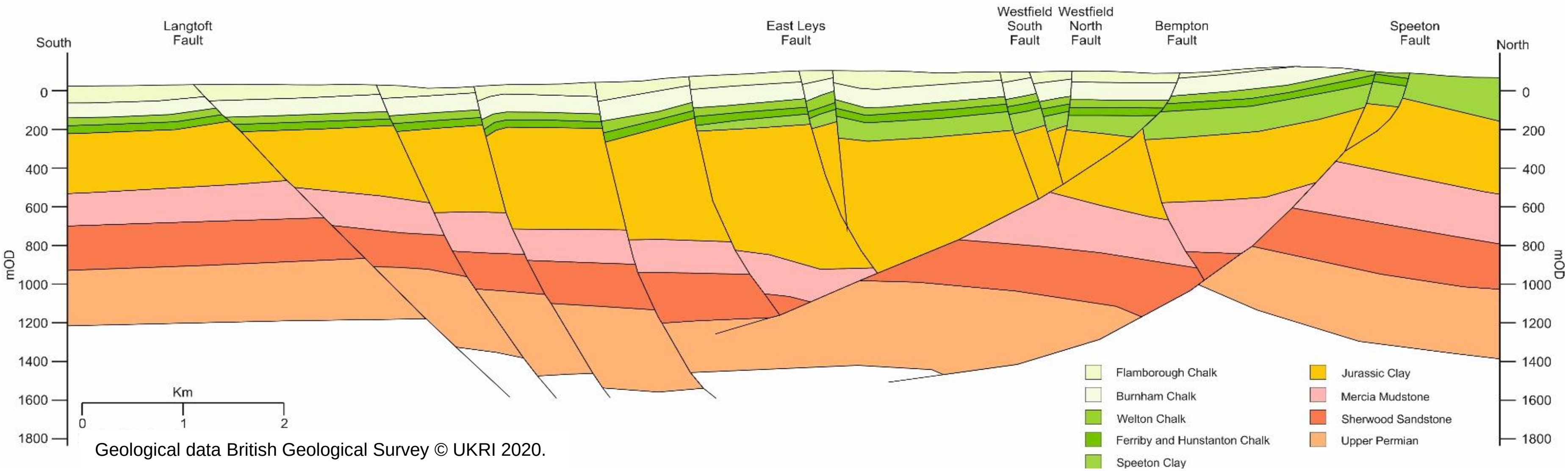
- West of the Hunmanby Trough the FHFZ is bound in the south by the steep, north-dipping Langtoft Fault and in the north by the south-dipping listric Bempton Fault. At depth the Bempton Fault roots into the Permian Zechstein Salts where it forms a low-angle detachment. It is unclear how far south this extends. South of the Bemtpon Fault, the Foxholes Fault is also listric at depth and may splay from, be truncated by or truncate the Bempton Fault
- North of the Langtoft fault three steeply-south-dipping faults form a graben feature, the Langtoft Trough, which has been reactivated during inversion to accommodate reverse displacement on some of the faults.
- Two further grabens, the Foxholes and Bempton Troughs, are formed by north-dipping faults which link to the Foxholes and Bempton Faults at depth. Some of these faults have also accommodated reverse displacement.

# Eastern FHFZ



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- East of the Hunmanby Trough, the structure of the FHFZ is notably different. The FHFZ is bound in the south by the steep, north-dipping Langtoft Fault and in the north by the south-dipping, listric Bempton Fault. There is no evidence of an eastwards continuation of the listric Foxholes Fault. North of the Bempton Fault, the Speeton Fault is almost parallel to the Bempton Fault, although the deep interaction between the two faults is unclear.
- Between the Langtoft Fault and the Bempton Faults are several steeply north-dipping faults which accommodate predominantly normal displacement. Some of the more northern of these faults terminate against the Bempton Fault.
- A steep, north-dipping fault terminating against the Speeton Fault in the Sherwood Sandstone is truncated by the Bempton Fault, potentially suggesting that the Speeton Fault, and associated faults, are older than the Bempton Fault.
- Consecutively eastwards seismic lines suggest that the width of the FHFZ decreases significantly eastwards and the most eastwards onshore sections show termination of the Bempton Fault against the Langtoft Fault.
- The differences in the structure of the FHFZ east and west of the Hunmanby Trough suggest that the N-S trending have partitioned deformation across the FHFZ into two zones which have developed different structures.

# Groundwater Implications

- The veining and associated recrystallisation of the chalk has modified the porosity and permeability of the chalk. The recrystallised chalk and calcite veins are harder than the surrounding chalk and less prone to dissolution, reducing porosity and permeability and potentially causing a barrier to groundwater flow. However, hardened chalk that has been subjected to subsequent faulting may be more prone to shattering and the introduction of secondary permeability. This may particularly occur where the E-W faults of the FHFZ are intersected by the N-S faults of the Hunmanby Trough.

- There is an obvious difference in the amount of calcite veining and recrystallisation found along the faults in the northwest of the study area and the east of the study area, suggesting that the faults east of the Hunmanby Trough may have been subject to lower fluid flow and mineralisation. This is likely to lead to different groundwater flow regimes across and through the faults in different parts of the study area, and highlights the importance of a detailed understanding of the geology, faulting and mineralisation to understand groundwater flow and manage extraction.

- This updated geological and fault interpretation is intended to be used to assist with groundwater modelling and abstraction management.

Brecciation within a mineralised fault at Flamborough Head.

# Conclusions

- The Flamborough Head Fault Zone is composed of E-W trending normal faults which have been partitioned into two distinct zones with very different architectures by the N-S trending faults of the Hunmanby Trough;
  - West of the Hunmanby Trough the FHFZ is characterised by 3 grabens each of which is associated with a major deep-seated fault.
  - East of the Hunmanby Trough the FHFZ is characterised by steep, north-dipping faults which terminate at depth against the Bempton Fault.
- The width of the Flamborough Head Fault Zone decreases eastwards, suggesting individual faults accommodated more strain eastwards.
- The complex interaction of the Hunmanby Fault and Burton Flemming Fault System with the Flamborough Head Fault Zones suggests a history of reactivation of both fault zones.
- Inversion during the late Cretaceous – early Cenozoic has reactivated some of the normal faults as reverse faults to accommodate over 1.8 km of uplift.
- Mineralisation and recrystallization associated with faulting has altered the properties of the chalk within fault zones leading to differences in porosity and permeability which will affect groundwater flow in the aquifer which need to be considered in groundwater modelling and abstraction management.

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