

Controls on Fracture Geometry in Chalk*

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Abstract

Cretaceous chalk is an important reservoir unit in the North Sea, with a number of producing fields. Fractures are key to producing from chalk reservoirs due to the low permeability of the chalk matrix. Most chalks are heavily fractured, but the geometry and distribution of the fractures can be highly variable. Understanding the controls on fracture geometry and distribution is therefore vital to predict fluid flow through the chalk reservoir. The aim of this paper is to use field data from chalk outcrops in southeast and northeast England to identify the main fracture geometries, and then to use various numerical and analytical modelling techniques to understand the controls on those geometries.

Two outcrops were studied for this project: Pegwell Bay in southeast England and Flamborough Head in northeast England.

Pegwell Bay

Pegwell Bay lies on the steep southern limb of the Thanet anticline, an E-W striking asymmetric chalk cored anticline approximately 12 km long and 6 km wide (Shephard-Thorn 1988). The anticline is thought to have formed passively by draping and differential compaction of the chalk over a pre-existing basement fault scarp (Ameen 1995); however, this basement fault was subsequently reactivated by late Cretaceous to Tertiary inversion (Vandycke 2002). Chalk from the Santonian to Campanian age Newhaven Chalk member of the Upper Chalk formation is exposed along a 500 m E-W oriented coastal section. The chalk here is exposed both in 20-30 m high cliffs and in a horizontal wave-cut platform up to 80 m wide, which allowed us to map the structures in the chalk in both cross section and plan view ([Figure 1](#)).

Pegwell Bay is cut by a series of small, regularly spaced, sub-parallel N-S to NNW-SSE striking faults, typically 10 m apart (shown in red on [Figure 1b](#)). These faults dip both E and W and are generally steep, with dips ranging from 60° to vertical. They have dip-slip displacements varying from a few cm up to 5 m, but slickenside orientation suggests that these faults have also undergone a significant amount of strike-slip deformation as well. We believe this occurred in response to the late Cretaceous to Tertiary regional inversion.

The chalk in Pegwell Bay heavily fractured, with fracture spacing typically 10-50 cm. The majority of the fractures comprise open, uncemented joints inferred to have Mode I (dilatant) displacement. The fractures were mapped out in detail along both the wave cut platform and the cliff sections, and were found to have two principal geometries:

- Localised fracture patterns formed around bends, tips and splays in the m-scale faults cutting the section. These often took the form of concentric rings of fractures, centered on the fault bend or tip and extending up to 2-3 m away from it, although more complex geometries were seen around fault splays. These fractures are genetically related to the larger faults, and are likely to have the effect of increasing the permeability in the damage zone around these faults; however, they will not contribute to fluid flow between the faults.
- Fracture corridors, typically 2-10 m wide and up to 60m long, containing a high density of fractures aligned sub-parallel to the corridor, typically 2-20 cm apart and with high connectivity. Although they are frequently oblique to the m-scale faults and extend a long distance away from them, they usually originate at bends, tips and splays in these faults and hence are thought to be related to these in some way. They are likely to provide key fluid flow pathways through this chalk unit, often providing connectivity between the meter scale faults and their damage zones.

Flamborough Head

Flamborough Head is a 6 by 3 km headland jutting into the North Sea on the east coast of Yorkshire. It lies along the E-W trending boundary between the Jurassic to Lower Cretaceous Cleveland Basin, to the north, and the relatively stable Market Weighton Block to the south. The hinge zone between these two features is formed by the Howardian Hills - Flamborough Fault Belt, a 10 km wide E-W trending fault zone that passes directly underneath Flamborough Head (Kirby and Swallow 1987). The Upper Cretaceous chalk was deposited as a post rift blanket deposit over both the Cleveland Basin and the Market Weighton Block, but subsequent tectonic activity has caused reactivation of the underlying faults and several episodes of deformation in the overlying chalk (Starmer 1995).

The chalks from northeast England are consistently denser and less porous than those from southeast England, suggesting that they have been buried deeper (up to 2,000 m depth); in this respect, they are more similar to the chalk reservoirs of the North Sea. These chalks also typically have higher UCS, tensile strength and Young's Modulus than those from southeast England (Bell et al. 1999). Strata from the Turonian to Santonian age Welton, Burnham and Flamborough Chalk Formations are exposed along the north coast of Flamborough Head, and are accessible in three bays (Thornwick Bay, North Landing and Selwicks Bay) where they are exposed in both cliff section and wave cut platforms ([Figure 2](#)). Selwicks Bay also contains a large (20 m-throw) normal fault formed during one of the late tectonic reactivation phases, characterised by a 10 m wide core of breccia and crystalline calcite veins up to 30 cm thick (Starmer 1995).

Fracture corridors are also observed in Flamborough Head, although only in one locality, Selwicks Bay. However these differ from those in Pegwell Bay in two respects: firstly, they are narrower (typically 30-60 cm wide) and secondly they are mostly filled with crystalline calcite cement ([Figure 2a](#)).

In Thornwicks Bay and North Landing the majority of fractures belong to regional fracture sets, comprising regularly spaced open, uncemented fractures (spacings vary from 10 cm to 2 m) with a consistent orientation across the study area. Often 2-3 sets of oblique, crosscutting regional fractures can be seen. There are two distinct styles of regional fractures, which appear to be controlled by stratigraphy (see [Figure 2b](#)):

- The lowermost Welton Formation is characterised by large, inclined fractures, typically dipping at 60°, and often forming conjugate pairs. These fractures are generally long, cut through bed boundaries, and relatively widely spaced (1-3 m apart). They appear to have formed by Mode II shear failure, although the shear offset on them is mostly very small (<2 mm).
- The Burnham Formation is characterised by smaller, more closely spaced vertical bed-bound fractures (typically 20-50 cm apart). These are interpreted to have formed by Mode I tensile failure.

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The local fractures observed around the meter scale faults in Pegwell Bay are genetically related to the faults. We can model the localised stress anomalies that form around bends, splays and tips in the faults using either finite element or boundary element methods (see [Figure 1c](#)). In all cases we find a very close correlation with the observed fracture patterns, both in terms of distribution (heavily fractured zones correspond to regions of tensile stress) and orientation (the observed fractures follow the σ_{hmax} orientation predicted in the models).

The fracture corridors at Pegwell Bay also seem to be related to the faults, since they nucleate at the fault bends and tips, but they do not match the stress patterns generated by the numerical models; these mostly predict circular σ_{hmax} patterns in areas of tensile stress, consistent with the local concentric fractures but not with the outward-propagating fracture corridors. However increasing the fluid pressure in the fractures significantly can alter the stress patterns in the surrounding host rock, switching the σ_{hmax} pattern from circular to radial ([Figure 1d](#)). This suggests that the fracture corridors are formed by high-pressure fluids, possibly by a propagation process similar to that described by Olson (2004) but driven by fluid pressure rather than tensile stress. The fracture corridors at Flamborough Head would also be consistent with this origin: they are clustered around the 20 m-throw normal fault at Selwicks Bay and the crystalline calcite cementation in both the fracture corridors and the fault zone suggests the fracture corridors may have formed by the injection of high pressure calcite-rich fluid from the fault zone into the surrounding host rock.

The regional fractures at Flamborough Head most likely formed in response to a regional tectonic strain imposed during one of the episodes of late deformation. The difference in style between the inclined shear fractures and the vertical bed-bound dilatant fractures appears to be controlled by stratigraphy.

Porosity measurements on samples from the two formations suggest that the Burnham Chalk (porosity 12%) is more compacted than the Welton Chalk (porosity 17%). We can use a simple Mohr-Coulomb failure criterion combined with linear elasticity to calculate the strain at which tensile and shear failure will occur for chalk in different states of compaction, by using published data to estimate mechanical properties based on porosity (e.g. Bell et al. 1999). As [Figure 2c](#) shows, the failure mode varies for chalk with different porosities: at 1.4x

fluid overpressure, more compact chalk (porosity >13%) will fail in tension before it fails in shear, whereas more porous chalk will fail in shear before it fails in tension, which is consistent with the observed deformation style.

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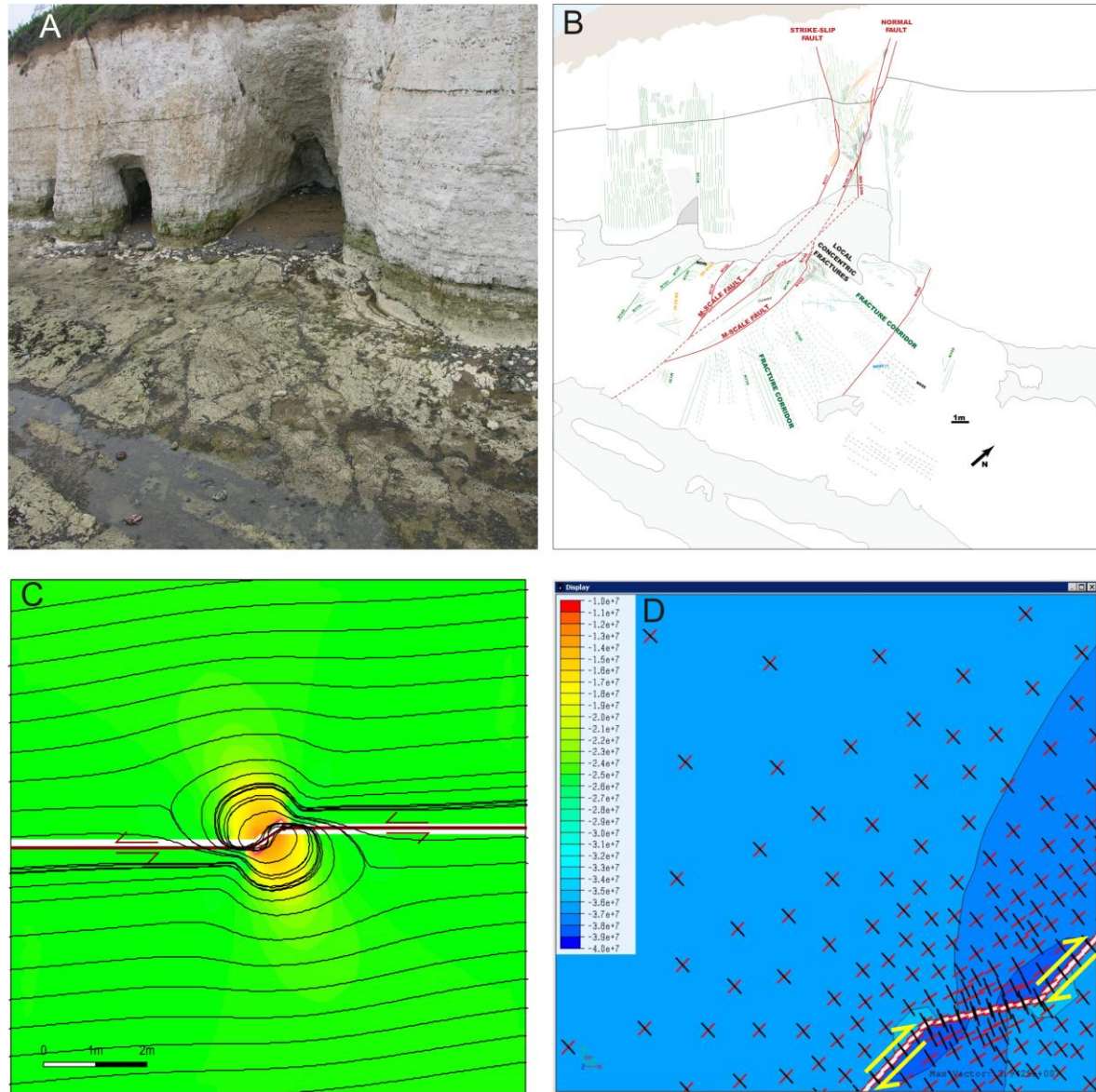


Figure 1. Photograph (A) and line drawing (B) showing fault and fracture patterns in a section of cliff and wave cut platform at Pegwell Bay, boundary element model showing the stress pattern around a releasing bend in a fault at normal fluid pressure (C) and finite element model showing the stress pattern around a releasing bend in a fault with 2x fluid overpressure (D); hot colours indicate tensile stress, cold colours indicate high compressive stress, and black lines indicate σ_{hmax} orientation.

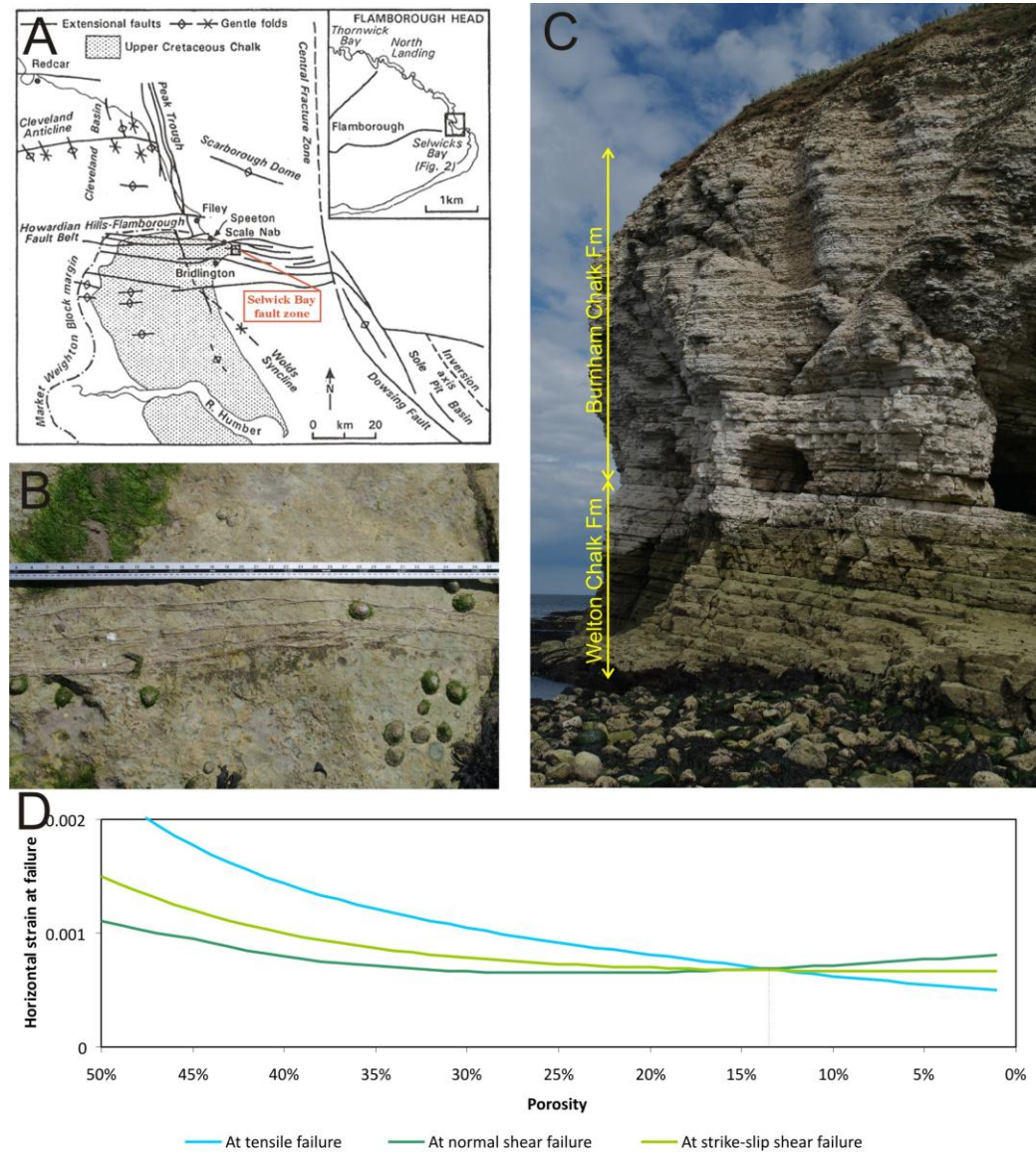


Figure 2. Regional structure around Flamborough Head, from Starmer 1995 (A), example of a calcite-cemented fracture corridor from Selwicks Bay (B), cliff section from North Landing showing the different regional fracture styles in the Welton and Burnham Chalk Formations (C), and chart showing the horizontal strain required to cause tensile, normal and strike-slip shear failure as a function of chalk porosity, assuming burial to 2,000m depth and 1.4x fluid overpressure (D).