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Natural hydraulic fractures and the mechanical stratigraphy of shale-dominated strata

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The aim of this study is to investigate stratigraphic variations in the spatial distribution and density of natural hydraulic and other fractures within oil mature, shale-dominated strata from the Cleveland Basin, northeast England. The studied interval includes the Pliensbachian Cleveland Ironstone and Toarcian Whitby Mudstone Formations. The Cleveland Ironstone Formation (ca. 25m thick) consists of silt- and mudstone units with discrete ironstone layers (seams). Ironstones account for 20% of the thickness of the formation. The Whitby Mudstone Formation is up to ca. 100 m thick; up to 2% of its total thickness consists of discrete calcium carbonate horizons, such as the Top Jet Dogger.

Natural hydraulic fractures, characterised by plumose marks and concentric arrest lines on fracture surfaces are ubiquitous throughout both formations; shear fractures with mm- to cm-scale displacements occur locally, particularly within silt- and mudstones. Natural hydraulic fractures locally contain thin, sometimes fibrous, calcite fills and are commonly observed to terminate at bedding plane interfaces between silt- or mudstone and carbonate beds. We have recorded fracture locations and apertures along 139 transects in both shale (i.e. silt- and mudstone intervals) and carbonate strata. Natural hydraulic and shear fractures, measured along transects up to 50m long within all lithologies in both formations, typically display uniform distributions. There is no correlation between spacing distribution and bulk extension in any lithology.

Median fracture densities recorded within the Cleveland Ironstone Formation are higher in intervening ironstone beds (<2.1 fractures per m in ironstone layers) compared with dominant shales (<0.9 fractures per m in silt- and mudstones). A qualitatively similar pattern occurs within the Whitby Mudstone Formation. However, the absolute values of median fracture density within different members of the Whitby Mudstone Formation range from 2.2–4.3 fractures per m, consistent with field observations that this formation is more highly fractured than the Cleveland Ironstone Formation. Semi-quantitative estimates of the mineralogical "brittleness index" suggest the highly fractured, clay-rich Mulgrave Shale Member of the Whitby Mudstone Formation has a low brittleness. Our results are therefore inconsistent with the widely held assumption that natural fracture density is greatest within units characterised by a high brittleness index.

We propose that stratigraphic variations in fracture densities are more likely to result from the different distributions of crack driving stresses; formations containing decimetre-scale, and most likely stiff, carbonate layers (such as the Cleveland Ironstone Formation) will have differing crack driving stresses compared with silt- and mudstone dominated successions (such as the Whitby Mudstone Formation). The high fracture density observed within the Mulgrave Shale Member is also consistent with propagation of natural hydraulic fractures driven by fluid overpressure caused by maturation of organic matter concentrated within this unit. The next step is to investigate the relative importance of maturation-driven overpressure v. mechanical heterogeneity by analysing the stratigraphic variations in fracture density within the underlying, organic-matter lean Redcar Mudstone Formation.