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Stratigraphic controls on fracturing in black and grey shale-dominated sequences

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Regularly-spaced arrays of opening-mode fractures develop in brittle layers (sandstone, limestone) that are embedded within a weaker matrix (shale) and subjected to layer-parallel extension. Where cut by tectonic faults, such brittle layers display a range of features including drag folds, shear fractures and rotated blocks, in addition to opening-mode fractures. In both cases, the weaker matrix deforms in a macroscopically ductile manner. Knowledge of the "mechanical stratigraphy" can therefore aid fracture prediction in subsurface reservoirs. A key question for unconventional hydrocarbon exploration is to what extent does the concept of mechanical stratigraphy apply to thick, shale-dominated sequences? The Toarcian (Lower Jurassic) Whitby Mudstone Formation (WMF) is a ca. 105 m thick, shale-dominated sequence that crops out within the Cleveland Basin, NE England and was deposited in $<$ 7.4 Myr. The WMF contains both black and grey shale intervals. The lowermost Mulgrave Shale Member ("Jet Rock"; *Harpoceras falciferum* Zone, *Cleviceras exaratum* Subzone) of the WMF is characterised by high total organic carbon (TOC $<$ 18 %), but low SiO_2, $Al2O_3$ and K_2O. TOC decreases, but SiO_2, $Al2O_3$ and K_2O all increase above the *exaratum* Subzone ("Bituminous Shales"). These geochemical variations are consistent with an upward increase in quartz and clay content within the Mulgrave Shale Member. The upper part of the Alum Shale Member ("Cement Shales"; *Hildoceras bifrons* Zone, *Zugodactylites braunianus* Subzone) is characterised by low TOC, $Al2O_3$ and K_2O, but high SiO_2 consistent with a high quartz and low clay content. The Jet Rock and Bituminous Shales are cut by regularly-spaced arrays of sub-vertical, calcite-filled opening-mode fractures that abut against sub-horizontal, bedding-parallel fractures with ca. 1 m vertical spacing. By contrast, the Cement Shales are characterised by arrays of dipping (dip $< 60^{\circ}$) shear fractures with consistent extensional offsets. We hypothesise that large fluid overpressures ($\lambda \rightarrow 1$) generated during clay diagenesis and/or kerogen maturation within the highly stratified (i.e. mechanically isotropic) Mulgrave Shale Member contributed to the development of bedding-parallel veins within the Jet Rock and Bituminous Shale. More speculatively, the spacing of the bedding-parallel veins may be controlled by metre- and sub-metre scale variations in organic and/or clay content throughout the Mulgrave Shale Member, which in turn may reflect primary sedimentary discontinuities. The regular spacing of compositional variations and discontinuity surfaces is likely to be a consequence of allogenic forcing mechanisms. By contrast, the SiO_2-rich, TOC- and clay-poor Cement Shales appear to be compositionally more homogeneous. The Cement Shales deformed under conditions of higher effective normal stress ($\lambda < 1$), giving rise to shear fractures with classic Andersonian geometries. Our observations suggest that stratigraphy exerts a strong control on fracturing within thick, shale-dominated sequences. However, the relationship between "mechanical stratigraphy" and fracture spacing and orientation appears to be more complex than in conventional clastic reservoir sequences.