Mini thief zones: Sub-centimeter sedimentary features enhance fracture connectivity in shales

Alistair T. McCay[1*], Zoe K. Shipton[1], Rebecca J. Lunn[1], and Julia F. Gale[2]

1. Engineering Geosciences and Geomechanics, Department of Civil and Environmental Engineering, University of Strathclyde, James Weir Building, Glasgow, G1 1XL.

2. The University of Texas at Austin, Bureau of Economic Geology, PO Box X, Austin, TX 78713-8924.

*. Now at, alistair.mccay@glasgow.ac.uk, Systems, Power and Energy, School of Engineering, University of Glasgow, Glagsow, G12 8QQ.

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Abstract

This study investigates the influences on fluid flow within a shale outcrop where the networks of two distinct palaeo-flow episodes have been recorded by carbonate-filled veins and green alteration halos. Such direct visualisation of flow networks is relatively rare and provides valuable information of fluid flow behaviour between core and seismic scale.

Detailed field mapping, fracture data, and sedimentary logging were used over a 270m^2 area to characterise the palaeo-fluid flow networks in the shale. Distal remnants of turbidite flow deposits are present within the shale as very thin (1-10mm) fine grained sandstone bands. The shale is cut by a series of conjugate faults and an associated fracture network; all at a scale smaller than seismic detection thresholds. The flow episodes utilised fluid flow networks consisting of subgroups of both the fractures and the thin turbidites. The first fluid flow episode network was mainly comprised of thin turbidites and shear fractures, whereas the network of the second fluid flow episode was primarily small joints (opening mode fractures) connecting the turbidites.

The distribution of turbidite thicknesses follows a negative exponential trend; which reflects the distribution of thicker turbidites recorded in previous studies. Fracture density varies on either side of faults, and is highest in an area between closely spaced faults. Better predictions of hydraulic properties of sedimentary-structural networks for resource evaluation can be informed from such outcrop sub-seismic scale characterisation. These relationships between the sub-seismic features could be applied when populating discrete fracture networks models, for example, to investigate such sedimentary-structural flow networks in exploration settings.

1. Introduction

Shales, mudstones or mudrocks (shale differentiated by higher fissility) account for approximately two thirds of the sedimentary rock covering the Earth's surface (Aplin and Macquaker 1999). Many industries require a solid understanding of the hydraulic properties of shales, for instance as top seals for conventional oil and gas reservoirs or CO_2 storage targets (Gaus 2010); reservoirs for unconventional hydrocarbon production (Gale et al. 2014); geological disposal sites for radioactive waste disposal (Kim et al. 2011); geothermal “duvet rocks” or high heat producing resources (Wilmot-Noller and Daly 2014). However, there are issues with being able to capture their permeability properties at the appropriate scale and then being able to upscale to whole reservoir perspective. Shales typically have low permeability (Dewhurst and Siggins 2006, Armitage et al. 2011, Aplin and MacQuaker 2011) and must be stimulated using hydraulic fracture treatments for hydrocarbon production. In order to enhance production it is advantageous if the hydraulic fractures connect the wellbore with higher permeability structures in the rock. Natural fractures, even if sealed, can be reactivated during treatments, and if open fracture networks are present, fluid flow will be strongly controlled by the linked natural and stimulated fracture network (Gale et al 2007).

Shale units can also be interbedded with coarser material, such as siltstone or sandstone, due to depositional cycles such as turbidite flows (figure 2.13, Bouma et al. 1962). However, the potential of such thin beds to act as high permeability pathways (sometimes referred to as thief zones) within a larger flow network has not previously been considered.

Fracture networks in tight rocks may be beneficial because they can increase completion quality in shale gas and tight gas wells (e.g. Glaser et al. 2013), or may be detrimental by providing leakage pathways (Gaus 2010). Fault zones in sedimentary environments have been extensively studied for their flow properties (Lehner and Pilaar, 1997; Yielding et al., 1997; Dockrill and Shipton 2010; Davatzes and Aydin 2003; Eichhubl et al., 2005) due to the role of faults in compartmentalisation of reservoirs and hydrocarbon trapping. Faults can also provide conduits for along-fault flow as evidenced by diagenetic alteration surrounding fault related fractures e.g. mineralisation induced colour changes (Eichhubl et al. 2009), mineralisation within fractures (Zhao et al. 2007, Kampman et al. 2012), modern springs (Fairley and Hinds 2004) and ancient CO_2 rich springs in the form of travertine mounds (Burnside et al. 2013).

Seismic techniques occasionally permit direct visualisation of fluid moving through faulted shales (i.e. seals) in the subsurface (Cartwright et al. 2007, Haney et al. 2005), but typically the structures controlling flow on the scale of the well are too small to be captured in reflection seismic data. On the other hand, cores from wellbores may only capture a small part of the permeability network and may not be representative of the larger scale. While many studies examine matrix permeability of core samples (e.g. Bolton et al. 2000, Aplin and Macquaker 2011), these are not representative of the bulk permeability of a fractured or faulted shale. Some studies have focussed on fault-related fractures, while others include the widely developed opening-mode fractures that occur in panels of rock away from faults (e.g. Lash and Engelder 2009, Gale et al. 2007, Evans 1994).

Outcrop analogue studies of fault and fracture systems in shale can be a useful scale bridge between core and seismic but are hampered due to the susceptibility of the rock to erosion leading to poor quality exposures. We investigated an exceptionally well-exposed shale unit hosting very thin (<1cm) sandy remnants of distal turbidite flows (Ingham 1978) and which is cut by sub-seismic scale faults. Distal regions of turbidite systems have previously been studied to understand their depositional environments (e.g. Crimes 1973), or the influence of turbidite sheet connectivity on hydrocarbon migration (Walker 1978). They are generally expected to form seals to hydrocarbon flow since any thin coarser grained layers lack vertical connectivity. We examine whether the sealing potential of shales in such distal turbidite regions is compromised by the presence of vertically connected subseismic fault and fracture networks in addition to the presence of rare injectites. Evidence is presented, collected from a distal portion of a turbidite system, of two separate fluid flow episodes identified by the presence of mineralisation and chemical alteration halos. A detailed study of the small scale sedimentary and structural features show that they interact, forming connected fluid flow networks through the mudstone. The results form the basis for a discussion about data collection strategies for aiding the detection and prediction of such networks in an applied setting.

2. Geological Setting

2.1 Field site location

The study area (figure 1), known as the Whitehouse Shore, is located in the southwest of Scotland, 3km south of the town of Girvan. Interbedded, steeply dipping beds of sandstones and shales are exposed in the intertidal zone below a raised beach. The shale unit of interest is swept clear of debris with each tide, leaving the rock surface smooth and accessible for about 2.5 hours either side of low tide.

figure 1 to go around here

The study area was chosen for two main reasons: 1) the unusually excellent exposure of mudrocks has undergone very low grade metamorphism, increasing resistance to erosion and therefore preserving the outcrop; 2) there is clear evidence of two distinct fluid flow episodes preserved in the rock. This site, the Whitehouse Shore, is a Site of Specific Scientific Interest (a UK classification of strict environmental and geological protection) and therefore no tools are permitted for sampling, all samples were from loose rock.

2.2 Sedimentary Setting

The Whitehouse Shore exposes Late Ordovician to Silurian sediments (figure 2) deposited within a submarine fan system that developed in a fore arc basin related to the closing of the Iapetus Ocean (Ince 1984). The Ballantrae Ophiolite, related to this closure, is located several km to the south of the field site. Sedimentology suggests sourcing from a magmatic arc with palaeocurrent indicators showing sourcing from the North West (Hubert 1966).

At this field locality greywackes, sandstones, siltstones, mudstones, shales and thin limestones were deposited in waters over 400m deep in the Late Ordovician (Lawson and Weedon 1992). Significant variations in sediment thicknesses of the underlying Benan Conglomerate suggest that the basin was bounded by active normal faults that controlled sedimentation on the fan (Ingham 1978). The Myoch Formation of the Upper Whitehouse Sub-Group is composed of predominantly green shale at its base overlain by red shale containing thin (often <1cm thick) sandstone bands. The Upper Whitehouse Sub-Group has been interpreted as deposited in a deep shelf and ocean floor setting distal to the submarine fan (Ingham 1978). This study focuses on the red shale member of the Myoch Formation, where the digenetic features are most clear.

figure 2 to go around here

To characterise the shale, grain size and composition were estimated from point counting on SEM images. The grain size of the shale ranges from clay to rare grains of very fine sand (< 5mm to 80mm), although most of the grains are silt (< 63mm) or smaller with approximately 50% of the grains being part of the clay fraction. The mineral composition of the red shale is 10% quartz, 63% feldspar, with biotite, chlorite and metal oxides making up the remaining 27%. The thin sandstone bands within the red shale have steep dips of 84^{o}-86^{o} and have tightly clustered strikes of NE-SW (figure 3). The sandstone grain size ranges from 17mm (medium silt) to a maximum measured grain size of 148mm (medium sand). No grading of grain size was observed in any of the sandstone bands. Point counting gives a clay content of the sandstone bands as 20% and the composition of the clasts as 56% quartz, 12% feldspar, with the remaining 32% composed of biotite, chlorite and metal oxides. The partial replacement of some biotite grains with chlorite indicates that the shale has undergone very low grade metamorphism.

Figure 3 to go around here

Sixty-nine sandstone band thicknesses were measured along a scanline perpendicular to the bands. Figure 4 shows a graphical representation of the sedimentary scanline. A digital caliper was used for their measurement and a histogram of the thicknesses is presented in figure 5. Almost all sandstone bands were under 1cm thick, but the thickest was significantly more at 7cm. Sandstone bands less than 1mm may be underestimated due to the difficulty of identifying such small features in the field. The distribution of sandstone band thicknesses is well described by a negative exponential distribution (figure 5). The sandstone bands represent a 3.6% net-to-gross of the total thickness of the red shale; similar ratios (2% sandstone) have been found in equivalent depositional environments (Basilici 1997).

figure 3 to go around here

figure 4 to go around here

Thin sandstone sheets and isolated lenticular lobes are typical of outer fan areas of muddy submarine deposition systems (Basilici 1997). In other studies, similar looking structures have been classified as thin-bedded sand-mud couplets of Facies C2.3 in the deep water facies classification of Pickering et al. 1986. Some of the sandstone bands are continuous and can be traced along strike for tens of metres, whereas others occur as horizons of individual, distinct lenses which are likely caused by current ripples (Pickering et al. 1986). For the purposes of this study the bands are classified as high connectivity (continuous for greater than 1m), medium connectivity (continuous for between 10cm and 1m), and low connectivity (continuous for less than 10cm). Although it should be noted that turbidites have been reported to have consistent connectivity for many kilometres (Plink-Blörklund and Steel 2004) significantly beyond the scale of this current study. Figure 6 shows how bands of these different connectivities tend to manifest in the field: even the low and medium connectivity bands can be laterally extensive and traceable for many tens of metres despite the apparent internally unconnected nature of the lenses. Although the poor connectivity could be an artifact of the 2D slice presented by the outcrop, i.e. the isolated lenses of a low connectivity sandstone bands are a part of a connected unit in 3D, information presented later (figure 12) shows that the classification is a key determinant of the fluid flow behavior of the sandstone bands. Rarely, sandstone injectites sourced from the sandstone bands cut through the shale perpendicular to bedding. These injectites are thin (<2cm), they typically do not repeat within 50m along strike of the bedding, and are only represented on the field study area in one location next to the main fault.

figure 6 to go around here

2.3 Structural context

The rotation of the beds to their current near vertical dip, was likely due to folding accommodating NW-SE compression during the Caledonian Orogeny. The subsequent formation of the Whitehouse Shore Thrust Fault and several smaller synthetic thrusts is evidence of ongoing NW-SE compression (Ingham 1970). These faults strike sub-parallel to bedding and are exposed as bed-parallel gullies containing a thin (less than two cm) brecciated zone, which can be traced for tens of metres across the exposure.

Conjugate dextral and sinstral strike-slip faults offset the beds and thrust faults. These have been interpreted as the final brittle deformation of the Caledonian Orogeny in the Late Silurian (Ingham 1978). The horizontal component of displacement on these strike-slip faults defined by offset of the subvertical bedding in the field site is usually less than 10m. This is a minimum value because the lack of slickenlines means that dip-slip displacement could not be determined.

The fault with the largest apparent displacement (labelled “main fault gully” in figure 2) was covered by coastal debris. A section of this fault exposed by seven volunteers with spades digging through coastal debris for a four hour tidal window, presented a fault core approximately 20cm wide with loose, uncemented brecciated shale from which individual pieces can be removed by hand. A splay fault off the main fault shows a breccia varying from 1 to 5cm wide bounded by slip surfaces. Both slip surfaces have sharp boundaries between the surrounding undeformed rock and the brecciated fault core. Sandstone bands are rotated clockwise into the fault, with some of this strain accommodated by shear fractures.

Shear fractures across the field site are orientated synthetic to the larger faults (figure 3c) and have horizontal offsets from several centimeters to a couple of millimeters. The shear fractures are primarily orientated WNW-ESE, synthetic to the main fault, with less common sets at NW-SE and NNW-SSE. Joints (fractures with no visible offset) are preferentially orientated to strike NW-SE (perpendicular to bedding) with some spread out to WNW-ESE and NNW-SSE (figure 3d).

3. Evidence for fluid flow

At the Whitehouse Shore there is clear evidence for two fluid flow episodes within the fractures and sandstone bands of the Myoch Formation red shale. The earliest fluid flow episode caused a phase of carbonate cementation. The second fluid flow episode caused diagenesis of the red shale into green halos around fractures and sandstone bands.

Carbonate cementation within this outcrop of the Myoch formation occurs in two forms: (1) as veins within fractures and (2) as pore-filling cement within sandstone bands (figure 7). Carbonate veins can be up to 2 cm thick (figure 7a) but are predominantly 1-3 mm thick (figure 7c). The carbonate fills a subset of fractures; other adjacent fractures and fractures of similar orientations may contain no cement. In the thicker veins multiple stages of cementation are visible. Carbonate was identified within the sandstone bands by the reaction with hydrochloric acid whereas the shale beds do not react.

Green halos surround a subset of the fractures and sandstone bands (figure 7). The halos typically extend less than one centimetre from fractures or bands and show a sharp contrast with the surrounding red shale. Green alteration in shale has previously been demonstrated to be due to the reduction of Fe3+ to Fe2+ (Mykura and Hampton 1984) along with transportation by diffusion of several minerals (Borradaile et al 1991). The red shale was likely deposited in oxidizing conditions, the overlying and underlying green shale layers are indicative of earlier and later reducing depositional conditions respectively. It is therefore likely that post-depositional fluid movement in the subsurface acted to reduce mineral oxides in the red shale. Regardless of the origin of the halos, this chemical alteration can be used to identify individual fractures that have acted as conduits for fluid flow (c.f Eichhubl et al. 2009).

Due to sampling restrictions, we were unable to sample the sandstone bands to determine which specific bands or parts of individual bands hosted carbonate cement. However, where checked, these bands always reacted with HCl, indicating the presence of carbonate. Therefor we have taken that those bands which were part of the second fluid flow episode creating the green halos also hosted the earlier carbonate-depositing flow episode.

figure 7 to go around here

There is clear field evidence that carbonate veins and cements preceded the formation of the green halos. Cross-cutting relationships showing green halo fractures terminating against carbonate filled fractures (figure 8a) are repeated throughout the field site, whereas the converse was never observed. Additionally, in places the margin of carbonate veins have acted as a focus for subsequent fracturing. Where this has occurred green halos are confined to only one side of the fracture (figure 8b). The carbonate vein has acted as a barrier, stopping the fluid reacting with the opposite fracture wall.

figure 8 to go around here

4. Spatial distribution of features that may have facilitated fluid flow

Figure 9 shows a map of the fractures and sandstone bands as identified in the field. The map was established by defining a one-metre square string grid over the field site. Each square meter was photographed and interpretations annotated directly onto the photographs in the field during several low-tide “windows”. These were then digitised and stitched together to make an initial map. The map was then ground-truthed during subsequent low-tides to ensure that stitching the images had preserved the geometry, and to ensure that fine details were included with particular attention to the connections between the features. All fractures displayed carbonate fill, green halos or both. Large sandstone bands all displayed green halos, small, unconnected bands that are too small to be included in the map sometimes had no halo.

The fracture density (defined as fracture mid-points per m^2) of carbonate filled and green halo fractures was counted using 46 circular scanlines; with diameters of 0.6 or 1.2metres (Mauldon et al. 2001). Scanline diameter was selected to be larger than the blocks between fractures to ensure an adequate rate of sampling (Rohrbaugh et al. 2002), and due to unpredictable tidal debris cover, locations were selected to ensure adequate exposure within the scanline area.

figure 9 to go around here

Shear fractures have orientations synthetic or antithetic to the main faults, and joints generally bisect the conjugate shear fractures (figure 3). The carbonate veins were often observed to be within the long, conjugate shear fractures. Conversely, green halos are more common around shorter NW-SE trending fractures, which tend to have no observable shear offset.

The field observations indicate that areas bounded by the main fault and splay fault have differing fracture properties. To aid discussion, the field area has been split up into “southern area” between South-West boundary and the Main Fault Gully, “central area” between the Main Fault Gully and the Splay Fault, and “northern area” between the Splay fault and the North-East boundary labelled on figure 10 as Second Fault Gully. Both the carbonate veins and green halo fractures are highest density in the central area between the main fault and the splay fault (figure 10). The two particularly high-density values for carbonate veins (labelled as “a” and “b” on figure 10) were caused by ladder geometry fractures between the splay fault and close proximity synthetic shear fractures. The carbonate veins also show relatively high density in the northern area whereas the green halos do not, this distribution can clearly be seen in the detailed fracture map of figure 9 where very few green halos are located in the northern area.

figure 10 to go around here

Orientation data were collected from 146 fractures within the detailed mapped area shown on figure 9. Figure 11 shows the orientations of the fractures divided into opening and shear mode (figure 11 b and c) and also by type of fluid alteration (figure 11, d, e, and f).

The sandstone bands are consistently steeply dipping (almost vertical) and strike SW-NE (figure 11 a). All fracture classifications (opening and shear mode and also both fluid flow alteration types) have strikes within 45° of NW-SE. However the orientations are not spread evenly within this area as some of the fracture types show particular clusters, highlighted on figure 11 (e.g. c1-c5 on Figure 11-c).

Joints and shear fractures have slightly different orientation distributions. The joint orientations are clustered around strikes of W-E (figure 11 c1 and c2), NW-SE (figure 11 c2 and c5) and also NNE-SSW (figure 11 c3). The shear fractures have much fewer orientation data than the joints, however the shear fractures appear to show a cluster striking N-S and also W-E (figure 11 b1 and b2 respectively). Although there are also some shear fractures striking NW-SE, there are proportionally less in this orientation than the joints.

The green halo fractures also show differences in orientation distribution to those fractures with carbonate fill. A high proportion of the green halo fractures were clustered around NW-SE strikes (figure 11 d2 and d4), and a smaller proportion were clustered around E-W strikes (figure 11 d1 and d3). While the carbonate filled fractures also have a small cluster around NW-SE strikes (figure 11 e2 and e4) there was a greater proportion clustered around E-W strikes (figure 11 e1 and e3). Additionally, the carbonate filled fractures also show a small cluster around a strike of N-S. The fractures which hosted both fluid flow events cluster around E-W strikes (figure 11 f1 and f3) and NW-SE (figure 11 f2 and f4) and a smaller proportion striking N-S.

figure 11 to go around here

Field evidence for fluid flow demonstrates that the architecture and the length of each sandstone band controls its connectivity to the wider fluid flow network. The internal connectivity of the sandstone bands (figure 6) strongly correlates with the likelihood of a sandstone band having hosted fluid flow; high connectivity sandstone bands were far more likely to be surrounded by green halos than the low connectivity sandstone bands (figure 12). Five of the six (83%) high connectivity sandstone bands hosted fluid flow compared with only nine of the twenty seven (33%) low connectivity sandstone bands. The lateral extent of the sandstone bands (see figure 12 for definition) also plays a role with the longer bands being more likely to host fluid flow. Fourteen of the thirty three (42%) high extent sandstone bands hosted fluid flow compared with only one of the five (20%) low extent bands (figure 12). Although extent is not as strong a relationship as connectivity, it is consistent with longer sandstone bands being more likely to intersect with other features that are open to fluid flow.

figure 12 to go around here

The sandstone bands are separated by irregular thicknesses of shale. If we assume that shale deposition is relatively constant, then the spacings between the sandstone bands may provide information about the timing of events which caused the turbidite flows depositing the coarser grained material. The spacing of the sandstone bands were measured to the nearest half centimetre using survey tape laid perpendicular to the bedding. The majority of the sandstone bands are spaced at intervals smaller than 0.1m (figure 13a), although two intervals are much wider than the others at 0.66m and 0.81m. A negative exponential trend could be fit to the spacing distributions (figure 13 b), although the two widest spacings were not used in this fit due to not being sufficiently sampled to show a trend at these wider spacings.

figure 13 to go around here

5. Connectivity of fluid flow features

Both carbonate and green halos are restricted to within or very close to the highest permeability features in the rock, demonstrating that the fluids that caused these diagenetic effects were confined to networks comprising fractures, thrust faults, strike-slip faults and sandstone bands. The map in figure 9 was used to explore the network connectivity of these features and the differences between the two recorded fluid flow episodes. Connectivity was defined by counting how many connections each mapped fracture had with the other fractures/thrusts/sandstone bands. The true 3D network may have more connectivity than the exposed 2D network, which was used to collect the connectivity data (Odling et al. 1999). However, the 2D network is the only viable way to collect field data on the connectivity between the features.

Figure 14 shows fracture connectivity for the three areas of the map, the southern, central and northern areas. When the fracture network is considered in isolation (i.e. not considering the sandstone bands or thrust faults) the majority of fractures have one or zero connections (figure 14a, b, c). For fluid flow to travel through such a potential fluid pathway then there must be at least two connections so as not to make a “dead end”. The first thing to note is that the fracture connectivity is lowest in the southern area, highest in the central area, and the northern area connectivity is approximately mid-way between the other two areas. This pattern of fracture connectivity correlates with the fracture density (figure 10). The higher fracture density of the central and north areas means that a higher proportion of fractures have two or more connections, compared with the southern area. However the central and northern area still have a median connectivity of 1, indicating that at least half of the fractures are still visible as “dead ends” in the exposed 2D fracture network. Such low values might usually be considered a poorly connected network, however the carbonate and green halos show that these fractures have been utilised as part of fluid flow episodes in the past.

figure 14 to go around here

If there had not been any diagenesis to provide evidence that the sandstone bands were utilised during flow episodes, then it would have been standard practice to examine the fracture network connectivity alone. In figure 15 the connectivity of the combined flow network is calculated by including the sandstone bands and thrusts when counting the connections of each fracture. This means that some fractures which may have previously been considered isolated or dead-ends are now connected to the flow network by intersections with sandstone bands. The full fluid flow network (fractures and bands) for the earlier carbonate-depositing fluid flow episode (figure 14) has higher connectivity than when considering the fracture network alone. This enhanced connectivity is shown by the lower proportion of fractures with zero or one connection. A similar pattern is seen for the fractures and bands in the later “green” fluid flow episode (figure 14 b). This indicates that the sandstone bands are connecting otherwise isolated fractures. The full network has a median number of connections per fracture of 2 in each area (figure 15) compared to the fractures alone (figure 15). It is also worth noting that even in the southern area, where fracture density is low, the influence of the sandstone bands is enough to triple the upper quartile number of connections per fracture.

figure 15 to go around here

6. Discussion

6.1 How has the network connectivity influenced fluid flow through the shale over time?

The bulk permeability properties of the shale will have been strongly influenced by the connectivity of the permeable features during the geological history of the shale. An increase in average fracture connectivity, due to fracture initiation or propagation would increase the likelihood of complete fracture pathways forming which transverse the shale layer. Conversely, should a key network connection close then the unit could return to more sealing behaviour. In the field example presented in this paper, the main fault could be considered such a key connection. If the main fault were closed to fluid flow (for instance by diagenesis), but other pathways remained open, then the shale would not become a seal despite a likely significant drop in overall bulk permeability. Examining the differences between the two fluid flow networks captured in this outcrop provides valuable insights into the hydraulic history of this shale.

Initially after deposition and burial, the shale formation would have had very low porosity (Aplin and Macquaker 2011) and therefore low permeability (Yang and Aplin 2007, Armitage et al. 2011). Prior to any fracturing of the rock, there would have been no hydraulic connectivity between the sandstone bands except for via the rare sandstone injectites. The first deformation features are the folding and bedding-parallel thrust faults. The folding resulted in the exposed Whitehouse Formation having sub-vertical dip. No fold-related fracturing was recorded by Ingham (1978) or by this study so new connections between sandstone bands may not have formed at this stage. The thrust faults are related to the Whitehouse Shore Thrust Fault which dips to the north-west (figure 2). During this tectonic event, the thrust faults may have become critically stressed (Barton et al. 1995) and could have provided potential fluid flow pathways between any sandstone band that was intersected and offset.

The next stage of deformation was the formation of the sub-seismic scale strike-slip faults (Ingham 1978). These faults and related fractures are well orientated to intersect with many of the sandstone bands. These intersections, and the fact that the fractures tend to be relatively large features cutting through much of the shale, formed a well-connected network. This network was then exploited during the first fluid episode which left evidence of carbonate precipitation. However this carbonate precipitation, or other possible effects such as stress changes, subsequently acted to close many of these larger faults and fractures such that for the second fluid flow episode, which created the green halos, there were fewer large features contributing to the fluid flow network. This effect is particularly strong in the Northern Area of the field site, where the density of fractures contributing to the fluid flow network decreases dramatically between the two fluid flow episodes (figure 10); although some fractures did remain open during both fluid flow episodes (figure 15 b). Conversely, the central area maintained high fracture density between the fluid flow episodes, this may be due to the closely spaced main fault and splay fault (figure 9). Such fault interaction areas have previously been recorded as having enhanced fluid flow rates caused by high fracture density (Curewitz and Karson 1997, Gartrell et al. 2004, Ligtenberg 2005), including in some shale gas reservoirs (Gale et al. 2007).

The significant drop in the number of conductive fractures of the Northern Area in the time between the two fluid flow episodes would normally be expected to cause a decrease in connectivity (Harris et al. 2003, Berkowitz 2005); particularly when compared to the central area which did not experience a significant drop in fracture density. However, despite the closure of the longer fractures after the first carbonate depositing flow episode, flow network connectivity was maintained because of the influence of the sandstone bands (figure 15) and the propagation of new fractures (figure 11 e). Although the flow network through the shale would now be more tortuous due to the interconnectivity required between the fractures and sandstone bands. Since the bands are perpendicular to the fractures, the result is a very well connected network for flow, and this unit did not behave as a seal. However, if only fractures had been considered, the density of open fractures would not have been enough to form connected networks through the shale, and the unit wrongly classified as sealing. In a sense, these high permeability sandstones are analogous to thief zones within seals or high permeability streaks observed in reservoir rocks (Felsenthal and Gangle 1975).

6.2 The distribution of the sandstone bands

Prediction of risks and opportunities remains the goal of much applied geoscience during hydrocarbon or geothermal exploration. The statistically constrained relationships (figures 5, 10, and 13) of the fluid-flow features indicate that such combined sedimentary-structural networks could be predictable.

Naturally, during any exploration a well-exposed outcrop will not be present, so it is important to ask how many of these features would have been picked up in wireline logs. From discussion with industry the limit of high resolution wireline logging is 5mm. Most of the sandstone bands are below this thickness and would therefore not be detected in an exploration setting; 82% of the sandstone bands with green halos had thicknesses below 5mm, whereas 78% of the bands with no halo (i.e. not connected to the network) had thicknesses below 5mm. There are no significant differences in ratio of number bands with green halos to those without, above or below this 5mm threshold, indicating that thickness is not key factor for fluid flow. Given the key role that the sandstone bands have within the flow network, it would be desirable to be able to be able to predict the thickness and spatial distribution of the bands with the greatest lateral extent, since these may be below detection threshold. Figure 5 showed that there is a relationship between the thicker and thinner bands in this study, but does this relationship hold for much thicker bands (e.g. >10cm)?

Studies of thicker turbidites (>10cm thickness) in submarine fan depositional systems report thickness-frequency distributions that are exponential (Sinclair and Cowie 2003), log-normal (Talling 2001) or power law (Hiscott et al. 1992) and that these distributions may be site specific. A complicated range of factors affect thickness distributions, such as location within depositional setting and magnitude of triggering event (Carlson and Grotzinger 2001). The variations in thickness distribution have also been attributed to channelised vs nonchannelised material flows resulting from depositional topography (Carlson and Grotzinger 2001) and to buoyancy changes as the turbidity current “thins” during transport and deposition (Pritchard and Gladstone 2009). Log-normal distributions have been attributed to under-sampling of thin beds, although Talling (2001) disputed whether this is due to under-sampling or a true reflection of material deposition.

The data presented in this study, in combination with those of Sinclair and Cowie (2003) suggest that the distribution of turbidite thickness within an individual turbidite sequence is well modelled by an exponential distribution. However, clearly, the parameter values that govern the exponential distribution vary. This is to be expected; for example, the statistics of turbidites triggered by floods are likely to vary between locations with differing climates, whereas the statistics of turbidites triggered by earthquakes will vary based on the earthquake magnitude-frequency distribution of proximal faults. Further, at a given site, turbidite thickness will decrease with increasing distance from the turbidite source (i.e. toward the edge of the fan). While a relatively small amount of studies have been conducted on the thickness of proximal and distal turbidites, even fewer have been published on turbidite thickness as a function of their lateral extent. To predict sandstone band thickness and spacing distributions in a turbidite sequence, not only should more data be collected from multiple outcrops (ideally including exposures both parallel and perpendicular to bedding) but these data should be pooled to develop generalisable statistical models based on turbidite triggering mechanism and location within the turbidite fan.

figure 16 to go around here

6.3 Modelling approach for such small scale fluid flow networks.

Discrete fracture network (DFN) modelling would be a typical solution to further investigate such a sedimentary-structural flow network. It is beyond the scope of this current paper to produce a DFN model but the observations and data can inform how a DFN model could be constructed.   This field study effectively presents a 2D window into the natural complicated 3D system, which would be modelled in a DFN. The observations made from the 2D outcrop, such as the central zone of high fracture connectivity surrounded by closely spaced faults, would be used to directly inform a modelled 3D network.

The sandstone bands would be added into the DFN as a ‘fracture set’. The set up of this hypothetical DFN requires statistics that characterised the ‘real’ fracture/joint sets as well as an extra set that represent the sandstone band statistics. Data on such sandstone bands could be determined from image logs. Thinner band distribution is related to the seismic-scale beds (stats as discussed in paper) but attention paid to the source mechanism and basin topography (Sinclair and Cowie 2003), turbidite sources, such as fault movement (e.g. Goldfinger et al. 2007) or storm events (e.g. Malamud and Turcotte 2006, Gorsline et al. 2000). The joint frequency could be inferred from shale bed thickness and fracture frequencies, location and orientation of seismic scale faults (e.g Bonnet et al. 2001, Manzocchi et al. 2009).

These sedimentary and structural statistical distributions would then provide a basis to statistically populate a DFN style model, used to characterise bulk permeability properties of the unit. The field observations in this paper are a vital scale-bridge between core data (which does not give bulk rock properties) and seismic data (which cannot detect small but important network features) to inform how features in such networks interact to create fluid flow systems.

7. Conclusions

Mineral precipitation and diagenetic alteration has allowed tracing of pathways of palaeo-fluid flow episodes in the Myoch Formation at Girvan, Scotland. Such fluid flow is expected to be confined to the fracture networks within such low permeability rock. This study demonstrates that very thin (<1 cm) and relatively poorly connected sandstone layers can act to enhance the fracture connectivity. If these sandstone bands played link otherwise isolated fractures, the bands would have played a crucial role in creating a connected network for fluid flow through the shale. The otherwise poorly connected fractures would not have been able to host such fluid flow without these sandstone bands alone. It is possible that such sedimentary structures in shales may be one route to forming sweet spots in shale gas reservoirs.

Sampling of such thin sandstone bands is confounded by their low thickness (below the resolution of wireline logging tools) and poor outcrop exposure, there is also a relative paucity of data on such thin layers. However the thin sandstone bands which are below the thickness of resolution show statistical distributions related to the thicker (>5mm) detectable bands in this study .

Although such fine-scale combined structural-sedimentary flow networks may seem too complex to realistically develop useful prediction methods, the observations in this paper suggest each of the important statistical properties of such fluid flow networks could be constrained, improving prediction of seal and fluid flow behaviour in similar settings.

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