Journal of Structural Geology 74 (2015) 64–80

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Influence of structural position on fracture networks in the Torridon Group, Achnashellach fold and thrust belt, NW Scotland

Hannah Watkins*, Robert W.H. Butler, Clare E. Bond, Dave Healy

Geology & Petroleum Geology, School of Geosciences, University of Aberdeen, Kings College, Aberdeen, AB24 3UE, UK

ARTICLE INFO

Article history:
Received 17 December 2014
Received in revised form
19 February 2015
Accepted 1 March 2015
Available online 10 March 2015

Keywords:
Fracture
Strain
Structural position
Tight sand
Fold and thrust belt

ABSTRACT

In fold-and-thrust belts rocks undergo deformation as fold geometries evolve. Deformation may be accommodated by brittle fracturing, which can vary depending on structural position. We use 2D forward modelling and 3D restorations to determine strain distributions throughout folds of the Achnashellach Culmination, Moine Thrust Belt, NW Scotland. Fracture data is taken from the Torridon Group; a thick, coarse grained fluviatile sandstone deposited during the Proterozoic. Modelling infers a correlation between strain and simple curvature; we use simple curvature to infer how structural position and strain control fracture attribute variations in a fold and thrust belt.

In high curvature regions, such as forelimbs, fracture intensities are high and fractures are short and oriented parallel to fold hinges. In low curvature regions fractures have variable intensities and are longer. Fracture orientations in these regions are scattered and vary over short distances. These variations do not relate to strain; data suggests lithology may influence fracturing. The strain history of fold structures also influences fracturing; structures with longer deformation histories exhibit consistent fracture attributes due to moderate-high strain during folding, despite present day low curvature. This is in contrast to younger folds with similar curvatures but shorter deformation histories. We suggest in high strain regions fracturing is influenced by structural controls, whereas in low strain regions lithology becomes more important in influencing fracturing.

1. Introduction

Fractures in fold and thrust belts are often thought to form synchronously with folding and therefore fracture pattern variations may be expected to relate to structural position on the fold. Understanding the mode of fold formation and strain history is critical for prediction of fracture attribute variations, which can be used in a range of applications, including fractured reservoir exploration, carbon capture and storage, aquifer characterisation and civil and mining engineering. Many studies have been conducted to investigate how fracture attributes vary in carbonate thrust belts for hydrocarbon exploration, such as in the Zagros fold-and-thrust belt of Iran (McQuillan, 1973, 1974; Wennberg et al., 2006; Wennberg et al., 2007; Awdal et al., 2013), the Italian Apennines (Storti and Salvini, 2001), the Rocky Mountains of the USA and Canada (Ghosh and Mitra, 2009; Barbier et al., 2012) and the Northeastern Brooks Range, Alaska (Hanks et al., 1997). Studies on fracturing in sandstone thrust belts are much less well documented; examples include Florez-Niño et al. (2005) and Iñigo et al. (2012) who use fractured outcrops as analogues to low porosity, low permeability (tight) sandstone hydrocarbon reservoirs in the Sub-Andean thrust belt. Other examples include Hennings et al. (2000), Bergbauer and Pollard (2004) and Bellahsen et al. (2006), who investigate fracture distributions across sandstone anticlines in Wyoming, USA, and Guiton et al. (2003) determine fold-fracture relationships in folded Devonian sandstones, Morocco. This paper contributes to the limited studies on fracturing in sandstone thrust belts, using the Torridon Group of the Moine Thrust Belt, NW Scotland as an analogue for a tight fractured sandstone reservoir in a fold and thrust belt.

Fracture variations have been attributed to both structural and lithological controls (e.g. Nelson, 1985). It is widely acknowledged that fracture set orientation within a deformed region relates to the orientation of principle stresses during the formation of those

* Corresponding author. Tel.: +44 1224 273519.
E-mail addresses: h.watkins@abdn.ac.uk (H. Watkins), rob.butler@abdn.ac.uk (R.W.H. Butler), clare.bond@abdn.ac.uk (C.E. Bond), d.healy@abdn.ac.uk (D. Healy).

http://dx.doi.org/10.1016/j.jsg.2015.03.001

fractures. In a thrust related anticline we may expect to see up to four fracture sets (Price, 1966); the first being a joint set striking parallel to the fold hinge and dipping normal to bedding (J1, Fig. 1). This fracture set may be associated with outer-arc stretching during folding; regions of localised tensional stresses develop in the same orientation as regional compression, leading to fracture opening. A second joint set strikes perpendicular to the fold hinge and dips normal to bedding (J2, Fig. 1). This fracture set may be associated with localised extension due to elevated curvature on a plunging anticline.

The remaining fractures associated with a thrust related anticline are two sets of conjugate shear fractures (S1 & S2, Fig. 1) with an acute bisector parallel to the thrust transport direction. These fractures may form due to regional compression or localised inner-arc compression associated with tangential longitudinal strain folding (Ramsay, 1967). Often incomplete assemblages of these fractures are seen at outcrop where not all of the four fracture sets have developed. Cooper (1992) describes well developed J1 and J2 fractures parallel and perpendicular to the fold hinge and normal to bedding in the Upper Triassic Pardonet dolomites in the regions of the Sukunka and Bullmoose gas fields in NE British Columbia. Bedding-normal joints striking parallel to the fold hinge (J1) are documented alongside conjugate shear fractures with an acute bisector parallel to the transport direction (S1 & S2) (Muecke and Charlesworth, 1966) in folded Cardium Sandstones of the Canadian Rocky Mountain foothills. Complete fracture set assemblages have been documented from field examples such as in the Umbria-Marche Apennines (Di Naccio et al., 2005) and on the Khaviz anticline, SW Iran (Wennberg et al., 2007).

If fractures are stratabound (i.e. fracture height does not exceed the thickness of the mechanical layer within which the fracture has developed (Odling et al., 1999)), the height of a fracture is limited by the mechanical layer thickness (e.g. Wennberg et al., 2006), which limits fracture length (the exact relationship between mechanical layer thickness and fracture length depends on the aspect ratio of fracture length to height). Fracture length may also be structurally controlled; if strain increases during folding fractures may propagate in order to accommodate this strain. This would, in theory, lead to longer fractures in higher strained zones (Fig. 1); this relationship is shown by Ghosh and Mitra (2009) who calculate higher average fracture lengths in hinges than limbs. Fracture apertures may be controlled by strain; fracture widening accommodates increasing strain during folding, therefore we may expect to find wide apertures in high strain zones (Jamison, 1997) (Fig. 1). This relationship is seen in the Sub-Andean fold and thrust belt (Iñigo et al., 2012) where fracture apertures widen from the low strain backlimbs to the higher strain hinge and forelimbs. Fracture aperture is also though to correlate to fracture lengths; longer fractures tend to have wider apertures. This relationship is shown by Vermilye and Scholz (1995) who use many field locations across North America, and Ellis et al. (2012) who use data from the Torridon Group of NW Scotland.

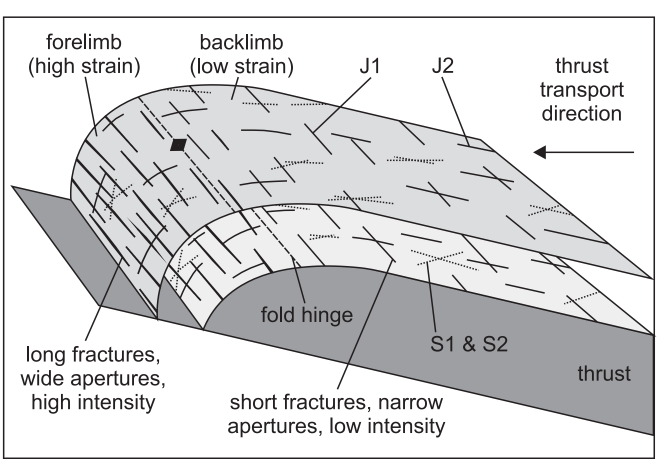

Fig. 1. Expected fracture characteristics on a thrust-related anticline. Steeper-dipping forelimbs are thought to have undergone higher strain meaning that fractures are better developed; fractures are longer and have high intensities in these regions. Four fracture sets are expected on thrust related anticlines; orientations relate to fold geometries and regional thrust transport direction (Price, 1966).

Controls on fracture intensity (fracture length per unit area in 2D) have been widely investigated through field-based studies. Many authors attribute variations in fracture intensity to rock strength and brittleness, which are controlled by rock composition, texture, grain size and porosity (e.g. Hugman and Friedman, 1979). Rocks with low competency such as clay-rich chalk, limestone or dolomite (Corbett et al., 1987; Ferrill and Morris, 2008) are often associated with low fracture intensities. Higher competency rocks such as dolomite-rich carbonates are associated with much higher fracture intensities (Barbier et al., 2012; Ferrill and Morris, 2008; Hanks et al., 1997; Hugman and Friedman, 1979; Ortega et al., 2010) as dolomite is a brittle mineral. Porosity is also seen to affect fracture intensity. In many cases higher fracture intensities are found in low porosity, high density rocks (e.g. Ameen, 2014), whereas in other examples higher porosities are associated with higher fracture intensities in carbonates (e.g. Barbier et al., 2012). Correlations are also seen between fracture intensity and carbonate grain size (Hanks et al., 1997; Hugman and Friedman, 1979), although this may be because coarser grained sedimentary rocks tend to be deposited with lower mud and clay content than finer grained rocks. As well as lithology, bed thickness is thought to influence fracture intensity; Mitra (1988) shows that fracture intensity is generally higher in thin beds.

Evidence for fracture intensity being structurally controlled is also seen; Bergbauer and Pollard (2004) report 5–10 times higher fracture intensities in folded sandstones & shales than in unfolded regions, although intensity values are constant on the fold itself. McQuillan (1973) also suggests fracture density is constant within fold structures of the Asmari Formation, SW Iran, providing bed thickness and lithology are constant. Many studies show an increase in fracture intensity in high curvature and high strain regions of individual fold structures in a range of lithologies (Hobbs, 1967; Jamison, 1997; Ortega et al., 2010), for example fracture intensity is often seen to be higher in fold forelimbs and crests than backlimbs (Barbier et al., 2012; Awdal et al., 2013).

We investigate variations in fracture set orientation, length, aperture, spatial distribution and intensity in a deformed tight (low matrix porosity and permeability) sandstone. We aim to determine whether fracture patterns are systematically structurally controlled within a fold and thrust belt, and therefore vary depending on their structural position.

2. Achnashellach Culmination

The Achnashellach Culmination is used as a field location for fracture data collection. The culmination is a fold-and-thrust belt in the southern Moine Thrust zone (Fig. 2b), which formed during the Caledonian Orogeny (c. 439-410 Ma, Mendum et al., 2009). Up to eight large-scale thrust-related anticlines of Torridon Group and Cambro-Ordovician sedimentary rocks (Basal Quartzite, Pipe Rock, Fucoid Beds, Salterella Grit and Durness Group) are exposed within a narrow, 3.5 km wide zone (Fig. 2a). The Achnashellach