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3D mechanical stratigraphy of a deformed multi-layer: Linking sedimentary architecture and strain partitioning

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ABSTRACT

Stratigraphic influence on structural style and strain distribution in deformed sedimentary sequences is well established, in models of 2D mechanical stratigraphy. In this study we attempt to refine existing models of stratigraphic-structure interaction by examining outcrop scale 3D variations in sedimentary architecture and the effects on subsequent deformation. At Monkstone Point, Pembrokeshire, SW Wales, digital mapping and virtual scanline data from a high resolution virtual outcrop have been combined with field observations, sedimentary logs and thin section analysis. Results show that significant variation in strain partitioning is controlled by changes, at a scale of tens of metres, in sedimentary architecture within Upper Carboniferous fluvio-deltaic deposits. Coupled vs uncoupled deformation of the sequence is defined by the composition and lateral continuity of mechanical units and unit interfaces. Where the sedimentary sequence is characterized by gradational changes in composition and grain size, we find that deformation structures are best characterized by patterns of distributed strain. In contrast, distinct compositional changes vertically and in laterally equivalent deposits results in highly partitioned deformation and strain. The mechanical stratigraphy of the study area is inherently 3D in nature, due to lateral and vertical compositional variability. Consideration should be given to 3D variations in mechanical stratigraphy, such as those outlined here, when predicting subsurface deformation in multi-layers.

1. Introduction

Understanding how deformation processes are impacted by the inherent compositional heterogeneity of the rock volume being deformed is a key question in structural geology. The complex interplay of stratigraphic heterogeneity and structural mechanisms is well documented at multiple scales of observation and in a range of tectonic settings. Studies have addressed this interaction at thin section (e.g. Hooker et al., 2013), outcrop (e.g. Lloyd and Chinnery, 2002; Butler and McCaffrey, 2004; Roche et al., 2012) and regional (e.g. Woodward and Rutherford, 1989; Pfiffner, 1993; Mitra, 2003; Ferrill and Morris, 2008) scales, and have focussed on extensional (e.g. Morris et al., 2009; Ferrill et al., 2007, 2016) and contractional (e.g. Couzens and Wiltschko, 1996; Farzipour-Saein et al., 2009) tectonic regimes, at a range of temperatures and depths (e.g. Amilibia et al., 2008; Druguet et al., 2009; Poblet and Lisle, 2011). The concept of mechanical stratigraphy, defined as the mechanical properties of units, their relative thicknesses, unit spacing and the nature of unit boundaries, has developed, from such studies, in an attempt to improve understanding of deformation patterns in multi-layers.

Mechanical stratigraphy, or the differences in mechanical properties through a given sequence, has long been known to influence the localisation of strain in contractional settings (Willis, 1893). This concept has been used to explain a range of structural features and patterns, and has been found to influence style of folding (e.g. Couples and Lewis, 1999; Bastida et al., 2007), disharmony in folds (e.g. Currie et al., 1962; Pfiffner, 1993; Mitra, 2003), the presence of thrust and fold detachments in mechanically weak layers (e.g. Couzens and Wiltschko, 1996; Tavani et al., 2008; Vergés et al., 2011), partitioned vs distributed strain (e.g. Couples and Lewis, 1999; Fischer and Jackson, 1999; Van Noorden et al., 2007), and the evolution of mechanical stratigraphy through progressive deformation (e.g. Hayes and Hanks, 2008). Much emphasis has been placed on the role of mechanical stratigraphy in influencing fracture distributions (e.g. Ladeira and Price, 1981; Corbett et al., 1987; Laubach et al., 2009), and the importance of considering stratigraphic heterogeneity in conjunction with structural attributes when making predictions of fracture distributions (Zahm and Hennings, 2009). The concept of mechanical stratigraphy has thus led to a refinement of mechanical models to aid in their predictive ability.

While the concept of mechanical stratigraphy to explain and predict structural behaviour is a powerful tool, these models are generally applied to continuous sedimentary sequences based on 2D sections

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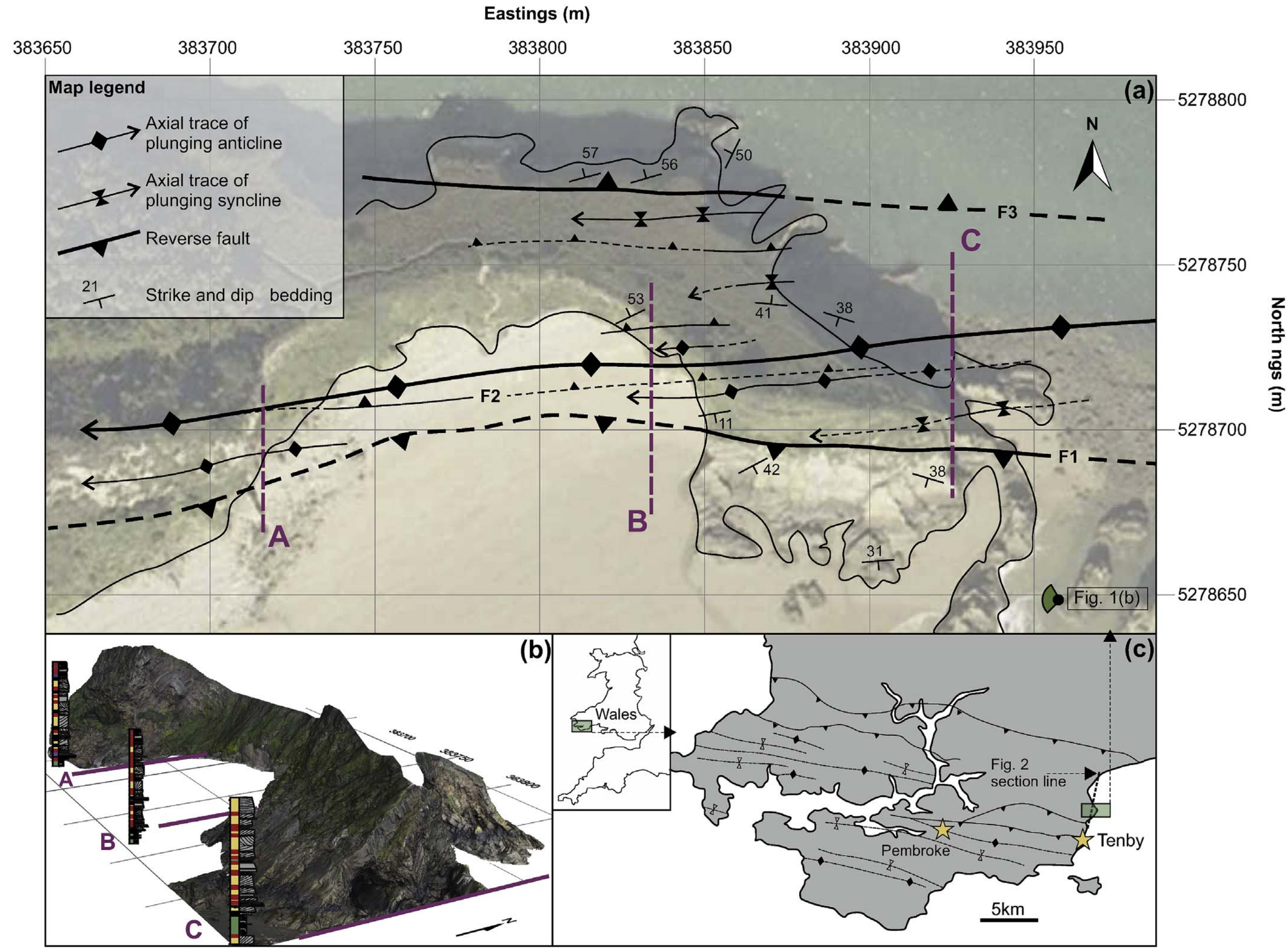

Fig. 1. Monkstone Point, Pembrokeshire. (a) Structural map of study area from in-field measurements, observations and virtual outcrop analysis. Purple lines mark cross-section locations (Fig. 8); green semi-circle denotes approximate camera location and field-of-view for Fig. 1b. Map coordinates: UTM Zone 31N. (b) Perspective view of Monkstone Point virtual outcrop, with locations of logs (see Fig. 4 for larger scale logs) and cross-section lines (see Fig. 8). (c) Summary structural map of Pembrokeshire (after Coward and Smallwood, 1984). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

through the stratigraphy. Mechanical layer and interface properties of rock units are commonly greatly simplified and presumed to be internally homogenous and laterally continuous. Only rarely is the presence of heterogeneities internal to units (e.g. Zahm and Hennings, 2009) or the superposition of structure on outcrop-scale sedimentary features (e.g. Hancock et al., 1982; Tringham, 1985; Nicol et al., 2002) acknowledged when considering stratigraphic-structure interactions, albeit in 2D. Some studies have addressed this interaction in 3D, using seismic data, e.g. Mansfield and Cartwright (1996) who describe the development of multiple thrust faults in different sedimentary layers, that later link into single through-going thrusts. Kristensen et al. (2008) and Roche et al. (2012) focus on, macro-mesoscale scale extensional faults highlighting complexities in fault evolution, branch patterns and relay development controlled in part by mechanical contrasts in the multi-layer systems studied.

This study assesses the effects of 3D depositional heterogeneity (stratigraphic architecture) on strain partitioning at an outcrop scale. Our example is from the contractional setting of Monkstone Point in Pembrokeshire, SW Wales (Fig. 1), which exposes a layered sequence of deformed clastic sediments. A genetic-link is predicted between the 3D stratigraphic architecture and the degree of strain partitioning within this multi-layer succession. Using sedimentary/structural logging, Structure from Motion photogrammetry, compositional analysis of samples and structural measurements we provide a detail analysis of the outcrop and document the extent and localisation of partitioned strain during contractional deformation. This strain partitioning manifests itself as different structural styles within and across layers in the outcrop. We discuss the findings of our work in the context of understanding 3D mechanical stratigraphy in non-planar multi-layer sedimentary successions, mechanical stratigraphy in contractional settings, and the consequent implications for subsurface prediction of structures.

2. Geological setting

Monkstone Point lies within the South Wales Lower Coal Measures Formation (312–313 MA), of the Upper Carboniferous (Westphalian), which is dominated by coal-bearing mudstones and siltstones, with minor sandstones present in the lower part of the succession (Jenkins, 1962; Williams, 1968; George, 1982; Waters et al., 2009). This sequence comprises part of the post-rift stratigraphy of SW Wales, post-dating units associated with Silurian and Devonian extension. The South Wales Lower Coal Measures Formation is interpreted as fluvio-deltaic in origin (George, 2008), and is characterized locally by distributary channels, coastal plain and delta slope deposits, and shallow marine sequences (Powell, 1989; George, 2000). Channel bodies within the lower part of the succession are characterized by erosive bases and are commonly cross-bedded. Minor seat-earths, overbank deposits and thin coal beds are distributed throughout the succession, and are often