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Exploring the seismic expression of fault zones in 3D seismic volumes

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ABSTRACT

Mapping and understanding distributed deformation is a major challenge for the structural interpretation of seismic data. However, volumes of seismic signal disturbance with low signal/noise ratio are systematically observed within 3D seismic datasets around fault systems. These seismic disturbance zones (SDZ) are commonly characterized by complex perturbations of the signal and occur at the sub-seismic (10 s m) to seismic scale (100 s m). They may store important information on deformation distributed around those larger scale structures that may be readily interpreted in conventional amplitude displays of seismic data. We introduce a method to detect fault-related disturbance zones and to discriminate between this and other noise sources such as those associated with the seismic acquisition (footprint noise). Two case studies from the Taranaki basin and deep-water Niger delta are presented. These resolve SDZs using tensor and semblance attributes along with conventional seismic mapping. The tensor attribute is more efficient in tracking volumes containing structural displacements while structurally-oriented semblance coherency is commonly disturbed by small waveform variations around the fault throw. We propose a workflow to map and cross-plot seismic waveform signal properties extracted from the seismic disturbance zone as a tool to investigate the seismic signature and explore seismic facies of a SDZ.

1. Introduction

Many existing interpretations of fault patterns in the subsurface imply relationships between fault geometry, displacement and strain distributed in the surrounding strata. Examples include fold-thrust systems (Boyer and Elliott, 1982; Butler, 1987; Butler and McCaffrey, 2004; Butler and Paton, 2010; Mitra, 1990; Suppe, 1983; Suppe and Medwedeff, 1990; Cardozo et al., 2003; Hardy and Allmendinger, 2011) and normal faults (Cartwright et al., 1995; Cowie and Scholz,1992; Childs et al., 1996, 2003; Jamieson, 2011; Walsh et al., 2003a,b; Long and Imber, 2010). Fully testing the applicability of these models demands determinations, if not of strain magnitudes then at least descriptions of the strain patterns. The challenge is to map distributed deformation using seismic data. Our aim here is to provide an interpretational framework that could be applied to mapping volumes of deformation in the subsurface using seismic facies concepts that are well-established for high resolution stratigraphic interpretations.

Conventional workflows for seismic interpretation commonly represent faults as discrete planar discontinuities across which stratal reflections are offset (Brown, 1996). Although this approach can greatly facilitate the creation of maps of stratal surfaces and hence the formulation of seismic stratigraphic models, this simplification can hamper understanding of subsurface structural geology (Hesthammer et al., 2001; Dutzer et al., 2009) and impact on the prediction of stratal juxtaposition and consequent models of fluid flow in hydrocarbon reservoirs (e.g. Faulkner et al., 2010). So there is much interest in developing better interpretative tools for seismic data that can predict the structure of complex fault zones, chiefly using seismic attributes (Jones and Knipe, 1996;Chopra and Marfurt, 2005; Cohen et al., 2006; Gao, 2003, 2007; Iacopini and Butler, 2011; Iacopini et al., 2012; McArdle et al., 2014; Botter et al., 2014; Hale, 2013 for a review; Marfurt and Alves, 2015). This contribution develops this theme further. We focus on two examples, one a normal fault zone (Taranaki Basin, New Zealand) and another a thrust zone (deep-water Niger Delta), using single and combined seismic attributes. Although these approaches are widely used to predict stratigraphic geometries in the subsurface,

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they have hitherto seen little application to the structural interpretation of seismic data. Therefore we outline the geophysical basis for the methods here – with greater detail reserved for the appendix.

Some of the issues affecting structural interpretation of faults are exemplified in Fig. 1. While some parts of the data appear to show discrete offsets across narrow zones where seismic amplitude is greatly reduced, other levels show broader areas of amplitude reduction. This could represent zones of more broadly dispersed deformation, such as are found in fault relays (Childs et al., 1996, 2003; Walsh et al., 1991, 2002, 2003a,b). An indication of these broader deformation zones is manifest here as the folding of stratal reflectors both in the hangingwall and footwall to the fault zone.

To further guide our studies, we refer to outcrop analogues for deformation structures developed in sandstone-shale multilayers (Fig. 2). In these small-scale situations, the deformation is very rarely focused onto a single fault surface. Although a single sub-planar discontinuity can commonly be identified upon which much of the displacement has been accommodated, this principal structure generally has other deformation surrounding it. For the thrust structure shown here (Fig. 2a), deformation includes folding, so that strata are locally sub-vertical, and include deformation fabrics (weak cleavage) and secondary faults. In the case of the fault example (Fig. 2b), although the bedding are gently folded, arrays of secondary faults with variable dipping orientation (Fig. 2c) create offsets of strata on various scales. In both cases the deformation away from their respective principal faults disrupts bedding. Consequently we infer that if these examples are representative, suitably up-scaled, for those in the subsurface, these secondary structural features should be manifest in seismic data. The challenge is to identify and interpret these – at least to isolate stratal volumes where these secondary deformations are most concentrated. This is the central aim of our paper.

2. Methodology

2.1. Seismic attributes

Attributes are measurements based on seismic data such as polarity, phase, frequency, or velocity (Dorn, 1998). They are calculated through signal and image processing algorithms and are used for both qualitative and quantitative interpretation of seismic dataset. Our approach uses seismic attributes to provide information carried by the seismic signal that is otherwise not used in conventional seismic mapping. When interpreting stratigraphic features such as channels and marginal units to carbonate reefs (Marfurt and Chopra, 2007), different attributes are combined to create so-called "seismic texture" maps. The term "seismic texture analysis" was first introduced by Haralick et al. (1973). Love and Simaan (1984) subsequently applied the concept to extract patterns of common seismic signal character. The approach gained favor because sedimentary features with common signal character could be related to their inferred depositional environment (Fournier and Derain, 1995). Subsequently a plethora of seismic attributes and textures have been developed - using statistical measures to quantify stratigraphic interpretations by creating repeatable seismic facies to predict subsurface reservoir characteristics (Gerard and Buhrig, 1990; Evans et al., 1992; Gao, 2003, 2007; Schlaf et al., 2004; Chopra and Marfurt, 2005; West et al., 2002; Corradi et al., 2009). The 1990s saw 3D attribute extractions become commonplace in the interpretation work place. During this time seismic interpreters were making use of dip and

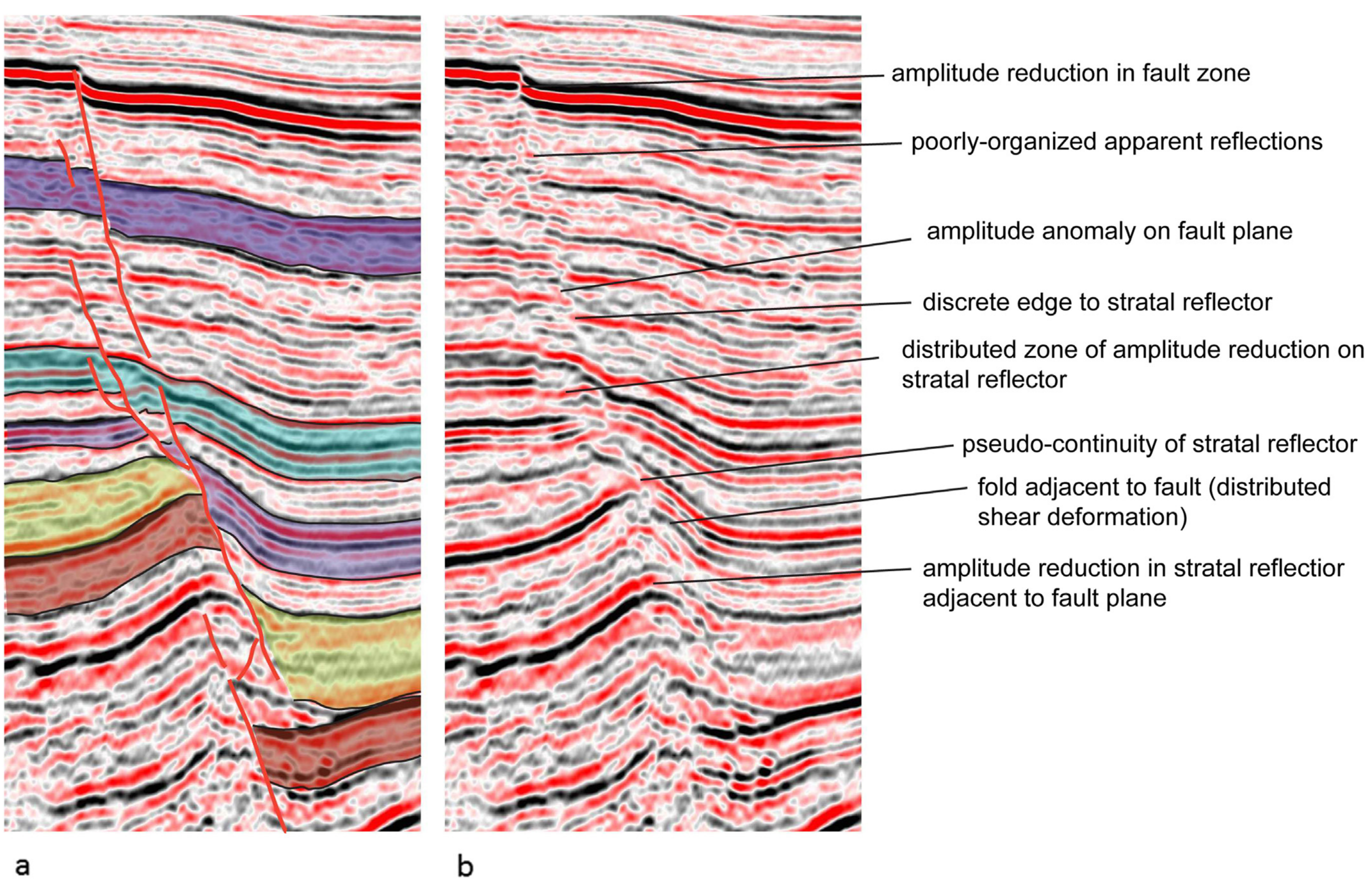

Fig. 1. a) Interpreted seismic image of a normal fault structure and related damage (North sea, Virtual SA library). b) Characterization of the main reflectors along the fault structure.