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A broader classification of damage zones

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A B S T R A C T

Damage zones have previously been classified in terms of their positions at fault tips, walls or areas of linkage, with the latter being described in terms of sub-parallel and synchronously active faults. We broaden the idea of linkage to include structures around the intersections of non-parallel and/or non-synchronous faults. These *interaction* damage zones can be divided into *approaching* damage zones, where the faults kinematically interact but are not physically connected, and *intersection* damage zones, where the faults either abut or cross-cut. The damage zone concept is applied to other settings in which strain or displacement variations are taken up by a range of structures, such as at fault bends. It is recommended that a prefix can be added to a wide range of damage zones, to describe the locations in which they formed, e.g., *approaching*, *intersection* and *fault bend* damage zone. Such interpretations are commonly based on limited knowledge of the 3D geometries of the structures, such as from exposure surfaces, and there may be spatial variations. For example, approaching faults and related damage seen in outcrop may be intersecting elsewhere on the fault planes.

Dilation in intersection damage zones can represent narrow and localised channels for fluid flow, and such dilation can be influenced by post-faulting stress patterns.

1. Introduction

The initiation, propagation, interaction and build-up of slip along faults creates a volume of deformed wall rocks around a fault surface called a *damage zone* (Cowie and Scholz, 1992; McGrath and Davison, 1995; Caine et al., 1996; Kim et al., 2004; Childs et al., 2009; Choi et al., 2016). The damage zone concept is useful because it relates localised zones of deformation to the structures that formed them. For example, Kim et al. (2004) define *tip*, *wall* and *linking* damage zones based on the location around the segmented faults in which they form (Figs. 1 and 2), while Choi et al. (2016, Fig. 3) define *along-fault*, *around-tip* and *cross-fault* damage zones based on their location around an exposed fault. Fault damage zones generally develop to accommodate strain or displacement variations along, around and between faults. Damage zones are areas of stress concentration and perturbation, within which deformation is concentrated and structures commonly have different frequencies and orientations than in the surrounding areas (e.g., Ishii, 2016), with different fault geometries and displacements (e.g., Scholz and Cowie, 1990). Thus they give useful information about the deformation histories and kinematics of the parent faults (e.g., Bastesen and Rotevatn, 2012; Rotevatn and Bastesen, 2014; Storti et al., 2015). Structures within damage zones also influence fluid flow along, across and around fault zones (e.g., Caine et al., 1996; Billi et al., 2003).

Damage zones generally show increased fracture frequencies and linkage. Fig. 3 shows damage zone around a normal fault zone in Miocene carbonates on Malta, which accommodated less than a metre of displacement (Pedley et al., 1976; Michie et al., 2014; Dimmen, 2016). Deformation, as indicated by branch intensities and connecting node frequencies (e.g., Morley and Nixon, 2016), is concentrated at fault bends and in areas of fault interaction. This deformation will tend to increase as the displacement increases and the fault system evolves. The examples we present are ancient, extinct, “static” faults, but the evolution of such structures can be inferred by observing cross-cutting and abutting relationships within individual fault zones, and by making about a range of different examples (e.g., Kim et al., 2003).

A wide range of structures can occur within damage zones, including: folds (e.g., McGrath and Davison, 1995, Fig. 5); antithetic faults (e.g., Kim et al., 2003, Fig. 5); synthetic faults (e.g., Kim et al., 2003, Fig. 10a); deformation bands (e.g., Fossen and Rotevatn, 2012;

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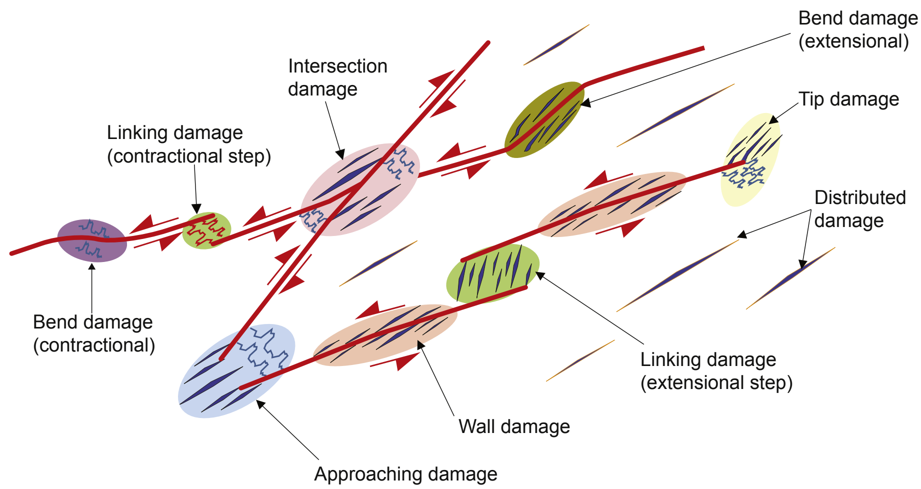

Fig. 1. Different types of damage zones, including our terms *approaching* and *intersection* damage zones. These, and the *linking* damage zone of Kim et al. (2004), are types of *interaction* damage zone. *Bend* and *distributed* damage zones, as defined in this paper, are also shown.

Qu and Tveranger, 2016; Rotevatn et al., 2016); veins (e.g., Caine et al., 1996); breccias (e.g., Billi, 2005, Fig. 2); joints (e.g., Mollema and Antonellini, 1999, Fig. 4); and stylolites (e.g., Tondi et al., 2006, Fig. 14). These structures give information about the kinematics, mechanics and history of the damage zones in which they occur.

In this paper, we generalise the Kim et al. (2004) model that deals with segmented faults that are sub-parallel and synchronous (Fig. 1). We describe a new category of *interaction* damage zones, which are created as two faults with any orientation and relative age approach each other and interact kinematically. The intention is not to add confusion through adding more terms, but to broaden usage of damage zones to include structures formed in a wider range of settings. We recommend that a descriptive term (qualifier) be prefixed to *damage zone* to describe the location or origin of the structures. Any classification scheme in geology may have the effect of simplifying a complex and subtle reality, but can still be of use in helping people describe and interpret a range of features. Our scheme probably excludes some damage zone types and includes some ambiguities. We hope, however, that the scheme helps in the understanding of structures that develop within fault networks.

The wider definition of damage zones presented here is important because it includes a greater range of fault relationships, including interaction between any two faults, irrespective of relative orientation or age. This broader usage, along with highlighting the role of post-fault deformation, mineralisation and stresses, is particularly helpful in predicting fluid flow related to fault interaction. For example, such interaction has been shown to control leakage from hydrocarbon reservoirs (e.g., Gartrell et al., 2004; Hermanrud et al., 2014; Simmenes et al., 2016).

2. Types of damage zones

Fig. 1 illustrates, schematically, the damage zone types classified by Kim et al. (2004), along with the broader range of damage zone types defined here. We use examples from the Mesozoic sedimentary rocks of Somerset, U.K. (e.g., Whittaker and Green, 1983; Willemse et al., 1997; Peacock and Sanderson, 1999; Peacock et al., 2017), from the Miocene carbonate rocks of Malta (e.g., Michie et al., 2014; Dimmen et al., 2017) and from the literature to illustrate the range of damage zones that can occur. These literature examples include a spread of different lithologies, tectonic settings and scales. Damage zones have been described from carbonate rocks (e.g., Billi et al., 2003; Kim et al., 2003), sandstones (e.g., Shipton and Cowie, 2003; Rotevatn et al., 2007), volcanic rocks (e.g., Hayman and Karson, 2007; Walker et al., 2013), intrusive igneous rocks (e.g., Mitchell and Faulkner, 2009), and metamorphic rocks (e.g., Wibberley and Shimamoto, 2003; Kristensen et al., 2016). Similarly, damage zones have been described in relation to normal (e.g., Shipton and Cowie, 2003), reverse (e.g., McGrath and Davison, 1995) and strike-slip (e.g., Kim et al., 2004) faults. Kim and Sanderson (2006) show that damage zones occur across a wide range of scales, and suggest that well-exposed small-scale damage zones observed in the field can be used to gain useful insights into deformation patterns along and around much larger faults, including those that influence or delimit hydrocarbon fields or plate boundaries.

2.1. Tip, wall and linking damage zones

Kim et al. (2004) define three classes of damage zone based on the locations with respect to the faults with which they are related (Figs. 1 and 2):

2.1.1. Tip damage zone

Area of deformation formed in response to stress concentration at a fault tip. Fig. 2(a) shows the tip of a sinistral fault that is in the form of calcite-filled pull-aparts connected by shear fractures. Within the damage zone, a set of stylolites take up contraction in the contractional quadrant of the fault tip, while wing cracks and veins take up extension. Other examples of tip damage zones are shown by Kim and Sanderson (2006, Figs. 4–8) and Rotevatn and Fossen (2011, Fig. 10).

2.1.2. Wall damage zone

Area of deformation resulting from the propagation of faults through rock, or from damage associated with the increase in slip on a fault. Fig. 2(b) shows calcite veins in the walls of a sinistral fault zone. It is possible that the veins were formed as an array prior to linkage to form the fault zone, but it is also possible the veins formed by friction along the fault. Other examples of wall damage zones are shown by Braathen et al. (2009, Fig. 5) and Srivastava et al. (2016, Fig. 4).

2.1.3. Linking damage zone

Area of deformation at a step between two sub-parallel coeval