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Fault damage zones

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Abstract

Damage zones show very similar geometries across a wide range of scales and fault types, including strike-slip, normal and thrust faults. We use a geometric classification of damage zones into *tip*-, *wall*-, and *linking-damage zones*, based on their location around faults. These classes can be subdivided in terms of fault and fracture patterns within the damage zone. A variety of damage zone structures can occur at mode II tips of strike-slip faults, including wing cracks, horsetail fractures, antithetic faults, and synthetic branch faults. Wall damage zones result from the propagation of mode II and mode III fault tips through a rock, or from damage associated with the increase in slip on a fault. Wall damage zone structures include extension fractures, antithetic faults, synthetic faults, and rotated blocks with associated triangular openings. The damage formed at the mode III tips of strike-slip faults (e.g. observed in cliff sections) are classified as wall damage zones, because the damage zone structures are distributed along a fault trace in map view. Mixed-mode tips are likely to show characteristics of both mode II and mode III tips. Linking damage zones are developed at steps between two sub-parallel faults, and the structures developed depend on whether the step is extensional or contractional. Extension fractures and pull-aparts typically develop in extensional steps, whilst solution seams, antithetic faults and synthetic faults commonly develop in contractional steps. Rotated blocks, isolated lenses or strike-slip duplexes may occur in both extensional and contractional steps.

Damage zone geometries and structures are strongly controlled by the location around a fault, the slip mode at a fault tip, and by the evolutionary stage of the fault. Although other factors control the nature of damage zones (e.g. lithology, rheology and stress system), the three-dimensional fault geometry and slip mode at each tip must be considered to gain an understanding of damage zones around faults.

Keywords: Damage zones; Fault tip; Fractures; Linkage; Strike-slip faults

1. Introduction

There have been a series of detailed descriptions of strike-slip faults and their damage zones in recent years (e.g. Segall and Pollard, 1983; Granier, 1985; Cruikshank et al., 1991a,b; McGrath and Davison, 1995; Martel and Boger, 1998; Kim et al., 2000, 2001a). For example, Kim et al. (2003) present a detailed description of damage zones in carbonate rocks around strike-slip faults with maximum slips of <1 m. In spite of this recent interest in damage zones, there is no published general account and systematic classification of damage zones. This paper synthesizes the results of these previous papers into a general classification of damage zones around faults. Emphasis is placed on strike-slip faults, but this classification scheme is extended to normal and reverse faults.

A *damage zone* is the volume of deformed wall rocks around a fault surface that results from the initiation, propagation, interaction and build-up of slip along faults (e.g. Cowie and Scholz, 1992; McGrath and Davison, 1995). The development of different structures within damage zones gives valuable information about fault propagation and growth (McGrath and Davison, 1995; Vermilye and Scholz, 1998, 1999; Kim et al., 2001a,b), fluid flow (Sibson, 1996; Martel and Boger, 1998), and about earthquake initiation and termination (Sibson, 1985; King, 1986; Aki, 1989; Thatcher and Bonilla, 1989).

In this paper, examples of exposure-scale damage zones around strike-slip faults are presented from:

- Crackington Haven, north Cornwall, UK (Kim, 2000; Kim et al., 2000, 2001a),

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- Rame Head, south Cornwall, UK (Kim et al., 2001b),
- Kilve, Somerset, UK (Peacock and Sanderson, 1995a; Kelly, 1998),
- Rush, near Dublin, Ireland (Dewey, 1966), and
- Gozo, Maltese islands (Kim et al., 2003).

Other examples from the literature are also discussed. The examples presented are shown with a dextral sense for ease of comparison (i.e. sinistral faults are reflected).

Various factors are likely to control the nature of damage zones around faults, including lithology, the dip of bedding relative to the slip direction of the fault, and the stress system. This paper, however, focuses on the importance of location around faults as a field-based classification of damage zones. A simple classification of damage zones is presented that is based on geometries of faults, the locations of their damage zones, and on the structures within the damage zones. The field examples described are likely to have an element of mixed-mode deformation (see Martel and Boger, 1998), but we have chosen examples of fault tips that we consider to be *dominated* by either mode II or mode III deformation.

2. Classification of damage zones based on their location

Fault growth commonly produces a *fault core* composed of slip surfaces and comminuted rock material, and also a broader volume of distributed deformation called the *damage zone* (McGrath and Davison, 1995; Caine et al., 1996; Vermilye and Scholz, 1998, 1999). Here, we divide damage zones into *tip*-, *linking*- and *wall-damage zones* (Fig. 1), based on position within and around a fault zone. A tip damage zone develops in response to stress concentration at a fault tip (e.g. Cowie and Scholz, 1992). Linking damage zones are caused by the interaction and linkage of fault segments in a relatively small region, and can develop a wide range of fracture patterns that depend on the nature of the interaction between the two fault segments. Wall damage zones may represent mode II and mode III tip damage zones abandoned in the wall rocks as faults propagate through the rock. They may also represent wall-rock deformation associated with the build-up of slip on faults.

This classification scheme becomes more complicated when fault planes and damage zones are considered in three dimensions, with each type of damage zone occurring at various locations in a fault zone (McGrath and Davison, 1995; Martel and Boger, 1998; Kim et al., 2003). There may be overlaps between the different classes, especially with tip damage zone commonly developing into linking damage zones, and both developing into wall damage zones as a fault evolves.

3. Mode II tip damage zones around strike-slip faults

The zone of fracturing in the volume of rock around a fault tip has been described in several papers (e.g. King, 1986; Ingraffea, 1987; Reches and Lockner, 1994; Vermilye and Scholz, 1998). Cowie and Scholz (1992) postulate that a rock will experience the highest stresses in the vicinity of a fault tip, and that damage produced by this stress concentration can be more intense than damage resulting from subsequent slip on a fault plane (Vermilye and Scholz, 1999). Martel (1997) suggests, however, that stresses need not be high in the vicinity of a fault tip.

Two end-member slip modes occur around the tip line of a strike-slip fault (Fig. 2; e.g. Paris and Sih, 1965). Mode II occurs at the lateral tips, and mode III slip occurs at up- and down-dip tips of a strike-slip fault. Between these two end-members, fault tips show mixed mode slips (Fig. 2). In this paper, we define mode II, mode III and mixed-mode damage zones that are dominated by these different slip modes. In this section, only mode II dominant tip damage zones are discussed. Mode III tip damage zones are discussed in Section 5.

The mode II (sliding mode) tip of a fault is where the tip line is normal to the slip direction (Fig. 2; Paris and Sih, 1965). Such fault tips are commonly exposed in map views of strike-slip faults, so have been described in many publications (e.g. Segall and Pollard, 1983; Granier, 1985; Petit and Barquins, 1988; Cruikshank et al., 1991a,b; McGrath and Davison, 1995; Willemse and Pollard, 1998). A variety of tip damage zones can occur at inferred mode II fault tips along strike-slip faults (Fig. 3). These tip damage zones can be sub-divided into four simple sub-divisions (Fig. 4), these being *dominated*, respectively, by wing cracks, horsetail fractures, synthetic branch faults and antithetic faults.

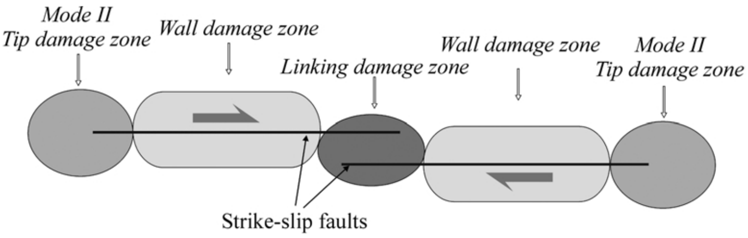

Fig. 1. Schematic diagram of the principal locations of damage zones around a strike-slip fault zone in map view. Damage zones are classified into three main types; tip damage zone, linking damage zone, and wall damage zone.

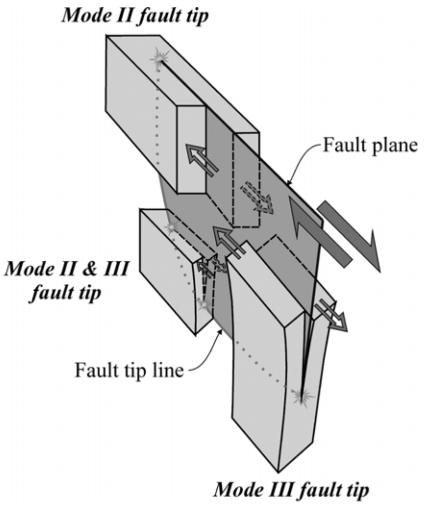

Fig. 2. Schematic model of fault tip modes (e.g. Atkinson, 1987, fig. 1.1). Mode II = in-plane shear or sliding mode; mode III = anti-plane shear or tearing mode; modes II and III = mixed mode. The star symbols indicate exposed tip points.

Wing cracks (Figs. 3a and 4a; e.g. Rispoli, 1981) occur where there is a rapid decrease in slip at the fault tip. They may form under low differential and confining pressures (Petit and Barquins, 1988) or under low effective stresses (Kim, 2000). *Horsetail fractures* or *pinnate fractures* (Figs. 3b and c and 4b; e.g. Granier, 1985; Hancock, 1985; Petit and Barquins, 1988; Engelder, 1989) are geometrically and mechanically similar to wing cracks, but are finer and more closely spaced with relatively low angles to the master faults. Horsetail fractures therefore tend to develop where slip dies out more gradually towards the fault tip than for wing cracks (Kim et al., 2000). Because these two types of tip damage zone fracture propagate as mode I cracks, a fault tends to grow along a curved or kinked path, which is locally parallel to the direction of maximum compressive stress at the time of faulting (e.g. Brace and Bombolakis, 1963; Erdogan and Sih, 1963; Segall and Pollard, 1983; Pollard and Segall, 1987).

Synthetic branch faults (Figs. 3d and 4c) are described by Chinnery (1966a,b), and this damage pattern occurs around the Dead Sea Fault (Fig. 3d; Butler et al., 1997). Similar structures are also called *splay faults* (Anderson, 1951) and *second order shears* (McKinstry, 1953). Branch faults have the same slip sense as the main fault, and may link with a neighbouring fault segment (Fig. 3d). Branch faults may combine with other structures in tip damage zones to produce complicated fracture patterns (Figs. 3d and 4f). For example, if branch faults combine with antithetic faults (Fig. 4e and f), the blocks between the faults may undergo block rotation (Fig. 3g and h).

Antithetic faults (Figs. 3e and 4d) are well exposed in damage zones on Gozo (Fig. 3e and g; Kim et al., 2003), and similar tip damage zones occur at Kilve (Fig. 3f; McGrath and Davison, 1995) and at Dasht-e Bayaz, Iran (Fig. 3h). These damage zones generally consist of several antithetic faults that splay out, increasing their length and spacing away from the fault tip (Fig. 4d; McGrath and Davison, 1995; Kim et al., 2003). Antithetic faults tend to be at ~30° to the inferred σ_1 direction and to be in the cohesive end zones (Kim et al., 2003) of fault tips, while wing cracks and horsetail fractures tend to be sub-parallel to the inferred σ_1 direction and to be in the extensional quadrants. Petit and Barquins (1988) model the geometry of such damage zones by fracturing glass plates. Some of these tip damage zones curve from the extensional quadrant into the contractional quadrant of the fault, away from the tip (Fig. 3f and g), and the wedge-shaped damage zone may combine with horsetail fractures or branch faults in the extensional quadrant (Fig. 4e and f). These structures are interpreted here as antithetic faults because further fracturing occurs at their tips, with the most prominent extension fractures branching off the antithetic faults (Fig. 3f and g; McGrath and Davison, 1995; Kim et al., 2003). The stress distribution at mode II tips is generally asymmetric across a fault, so the damage zones are asymmetric (Figs. 3 and 4).

Care is needed with this classification scheme for four reasons. Firstly, some tip damage zones show a combination of different types of minor fractures, the most common combination apparently being synthetic horsetail fractures or synthetic branch faults plus antithetic faults (Fig. 4e and f). Secondly, some tip damage zones show mixed mode (II and III) deformation (Martel and Boger, 1998; Figs. 2, 3e and 4g). Thirdly, the fractures evolve in a damage zone, e.g. with extension fractures developing shear as slip increases on the master fault. Fourthly, although the field areas described in this paper show wing cracks, horsetail fractures, synthetic branch faults and antithetic faults, other structures (e.g. joints, veins or deformation bands) may dominate in damage zone elsewhere. We believe, however, that it is useful to state the *dominant* structures within damage zones.

4. Linking damage zones in strike-slip fault systems

Linking damage zones commonly show relative complexity and intense fracturing compared with other types of damage zones (Zhang et al., 1991; Kim et al., 2003). They evolve between the interacting tips of adjacent faults (e.g. Kim et al., 2001a). Structures in linking damage zones are described by Segall and Pollard (1980, 1983), Terres and Sylvester (1981), Woodcock and Fischer (1986), Martel et al. (1988), Swanson (1988), Peacock and Sanderson (1995a) and Walsh et al. (1999). This section describes linkage between mode II tips of strike-slip faults.

4.1. Extensional steps

Various types of structures develop in extensional steps, including the following:

- *Extension fractures* (i.e. joints or veins) occur across a range of scales (Fig. 5a and b). Linkage between fault

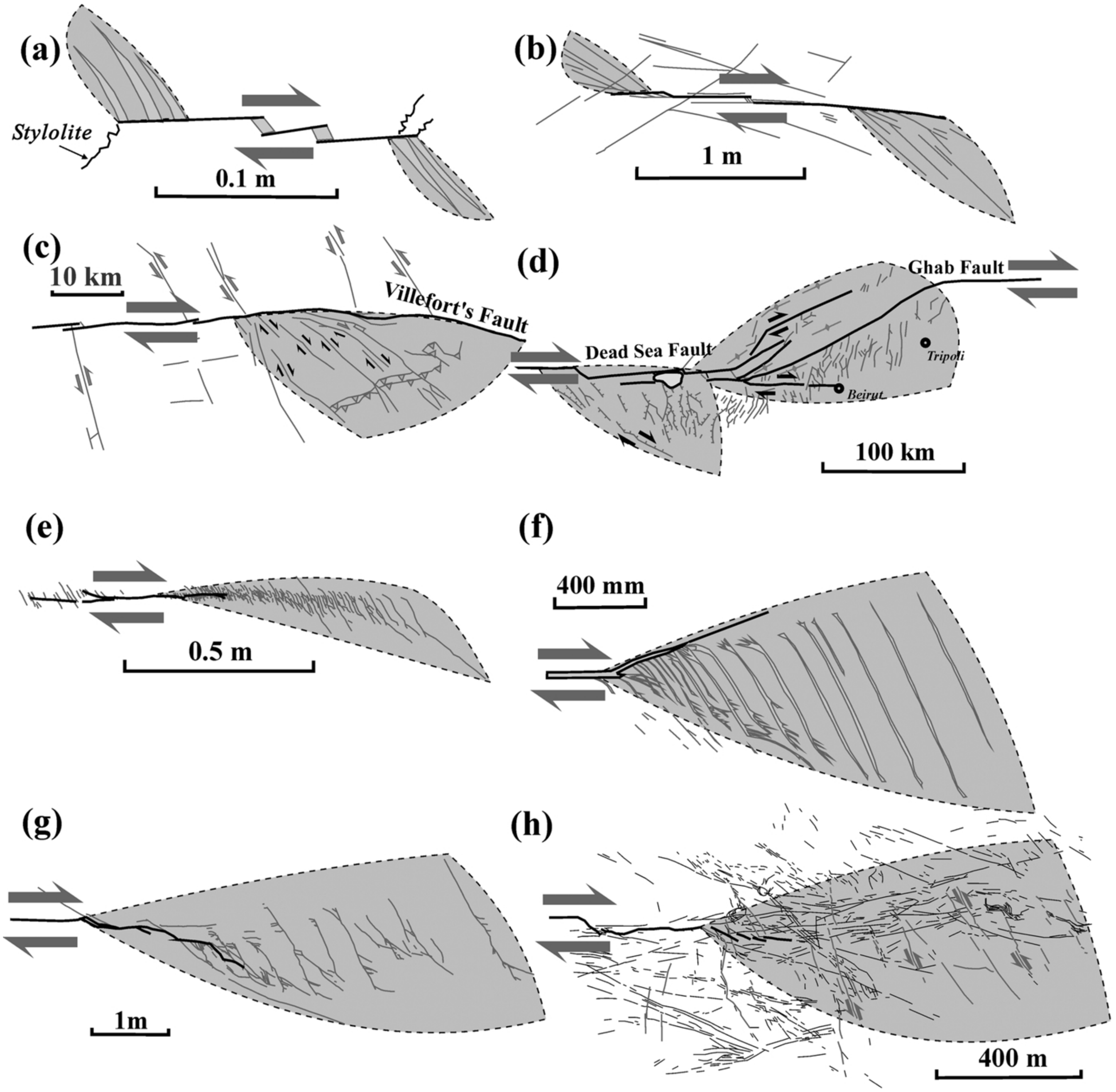

Fig. 3. Examples of damage zones at the mode II tips of strike-slip faults. Sinistral examples are reflected into a dextral sense for ease of comparison. Thick line = major fault, thin line = minor fault, shading = vein, which is part of the damage zone. The dotted shadings indicate tip damage zones. (a) Wing cracks in limestone from the Les Matalles outcrop, Languedoc region, France (Rispoli, 1981). (b) Horsetail fractures in slates at Crackington Haven, Cornwall, UK (Kim et al., 2000). (c) Horsetail fractures in schists and Carboniferous sedimentary rocks at Villefort's region, France (Granier, 1985). (d) Branch faults, normal faults and antithetic faults in the Dead Sea region, Lebanon (Butler et al., 1997). (e) Antithetic faults in limestone on Gozo, Maltese islands (Kim et al., 2003). (f) Antithetic faults in limestone at Kilve, Somerset, UK (McGrath and Davison, 1995). (g) Antithetic faults in limestone on Gozo, Maltese islands (Kim, 2000). (h) Antithetic faults at Dasht-e Bayaz, Iran (Tchalenko and Ambraseys, 1970).

segments is mainly controlled by extension fractures approximately parallel to the local σ_1 orientation, and the extension fractures are dominantly developed in the extensional quadrants of fault segments. The extension fractures abut the fault segments, and some link the two fault segments (Fig. 6a; e.g. Segall and Pollard, 1983; Peacock and Sanderson, 1995a).

- *Pull-aparts* are a type of extension fracture that open up between two fault segments (Figs. 5a and c and 6b; e.g. Aydin and Nur, 1982; Royden, 1985; Peacock and Sanderson, 1995b) due to increasing slip on the fault segments (e.g. Segall and Pollard, 1983). The shape of pull-aparts is controlled by the geometries of associated secondary fractures that form the pull-apart boundaries,

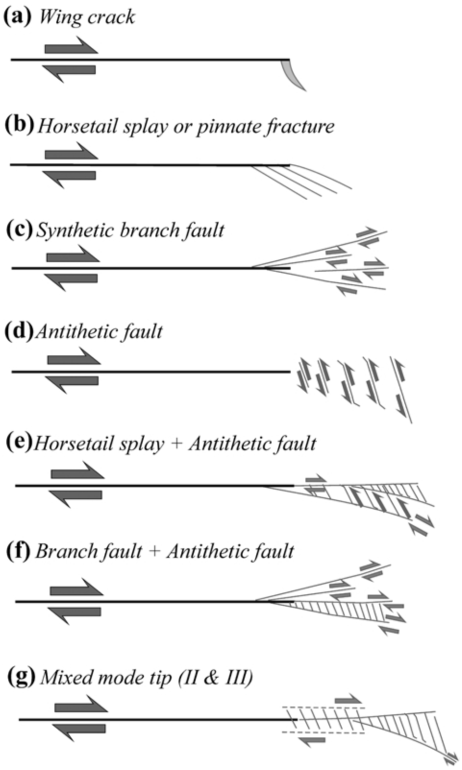

Fig. 4. Schematic illustrations of the main types of tip damage zones. The tip damage zones are divided into four major types (a–d), and some combined or mixed tip damage zones occur (e–g).

such as joints or veins, synthetic faults and antithetic faults (Kim et al., 2003).

- *Rotated blocks* can occur in extensional steps. In the example shown in Fig. 5d, blocks rotate as slip builds up along the boundary faults. Faults within the step are antithetic to the stepping faults (*master faults*), and extension fractures occur around the rotated block. The faults within the step initiate at an acute angle to the master faults, but can be rotated to an obtuse angle with the master faults (Fig. 5d). The blocks rotate synthetically, with the rotation angle increasing as fault slip increases. The rotation sense of the blocks in a step depends upon the stress conditions vertical to the master faults, the slip sense of the master faults and upon the sense of fault stepping, i.e. whether there is extension (synthetic rotation) or contraction (antithetic rotation) within the step (Martel et al., 1988; Gross et al., 1997). The block rotation in extensional fault steps displays a synthetic rotation sense with respect to the master faults (e.g. Fig. 6c). Blocks within a fault step can be rotated, which tends to create triangular openings where the rotating blocks intersect the master faults (e.g. Fig. 5d).
- *Strike-slip duplexes* (Woodcock and Fischer, 1986; Swanson, 1988) or *isolated lenses* (Kim et al., 2001b) with a single fault-bound block are shown in Fig. 5e and f. They are similar to *sidewall ripouts* (Swanson, 1989), and to *open eye-structures* (Fossen and Hesthammer, 1997). The strike-slip duplexes or isolated lenses (Fig. 6d) form at a fault step between two stepping fault segments. In extensional steps, voids or areas of extension are commonly formed around fault-bound blocks, and these spaces become filled with vein materials or basin sediments (Fig. 5c, e and f; Aydin and Nur, 1985). Duplexes are commonly breached by faults that connect the stepping segments (Fig. 5b; e.g. Cruikshank et al., 1991b).

4.2. Contractional steps

Structures developed in contractional steps include the following:

- *Rotated blocks* are shown in Fig. 5g and h, where the blocks show synthetic sense of rotation with the dextral master faults. Some of the faults in the steps between master faults show a sigmoidal shape, implying distributed simple shear within the step (Fig. 5g; Ramsay and Huber, 1983) or that fracture propagation paths have been influenced by interaction between neighbouring fractures (Olsen and Pollard, 1991). The antithetic slip sense of the faults within the step is indicated by smaller extension fractures branching off the fault tips.
- *Connecting faults* link two fault segments through a contractional overstep (Figs. 5i and 6f; e.g. Bürgmann and Pollard, 1994; Peacock and Sanderson, 1995a). The example shown in Fig. 5i shows two sub-parallel master faults with a strike-slip relay ramp (Peacock and Sanderson, 1995a) in a contractional step. Veins, antithetic faults and pressure solution seams also occur within the fault step. The strike-slip relay ramp has been partially breached by a synthetic fault. More evolved examples show completely broken fault steps, with a single irregular composite fault developed (Fig. 6f).
- *Strike-slip duplexes* (Woodcock and Fischer, 1986; Swanson, 1988; Cruikshank et al., 1991b) or *isolated lenses* occur in contractional steps at Rame Head (Kim et al., 2001b), although they are more commonly developed in extensional steps (Fig. 5e). Also, simple lenses are more common than strike-slip duplexes. This type of fault stepping geometry (Fig. 6g) also occurs in deformation bands in sandstone (Cruikshank et al., 1991b; Fossen and Hesthammer, 1997). A possible large-scale example occurs along the Coyote Creek Fault, which shows several fold axes and local uplift (Fig. 5j; Sharp and Clark, 1972; Segall and Pollard, 1980). Cruikshank et al. (1991b) suggest that the kinematics of these structures is similar to duplexes along thrust faults (Boyer and Elliott, 1982).

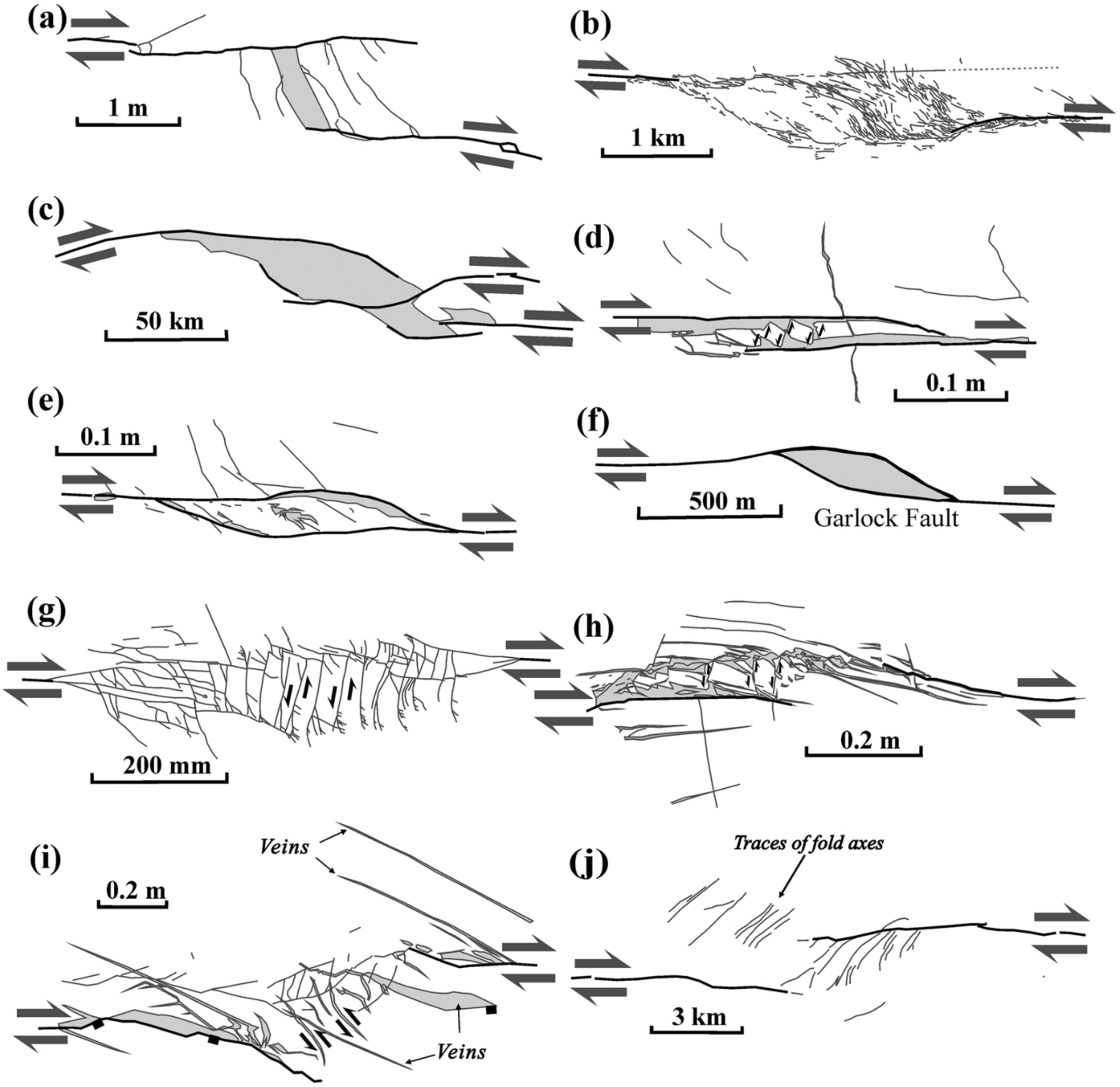

Fig. 5. Examples of linking damage zones in strike-slip fault zones. (a) Extension fractures and pull-aparts on Gozo, Maltese islands (Kim, 2000). (b) Extension fractures and strike-slip duplexes at Dasht-e Bayaz, Iran (Tchalenko and Ambraseys, 1970). (c) The Vienna Basin, Austria and Czechoslovakia, which is a pull-apart basin (Royden, 1985). (d) Block rotation at Kilve, Somerset (Kelly, 1998). (e). Strike-slip duplexes or isolated lenses at Rame Head, Cornwall, UK (Kim et al., 2001b). (f) Isolated lenses from Cantil Valley, California (Aydin and Nur, 1985). (g) Block rotation from Gozo, Maltese islands (Kim, 2000). (h) Block rotation from Kilve, Somerset, UK (Kelly, 1998). (i) Antithetic faults and connecting faults from East Quantoxhead, Somerset, UK (Peacock and Sanderson, 1995a). (j) Potential linkage in the Coyote Creek fault zone, California (Sharp and Clark, 1972). Thick line = major fault, thin line = minor fault, shading = vein in small scale examples and basin in large scale examples.

5. Wall damage zones around strike-slip faults

A wall damage zone can be distributed along the whole trace of a fault (Figs. 7 and 8), with such damage resulting both from the abandonment of tip damage zones and development of new structures in the walls of faults. We have observed three groups of such damage zones: (1) wedge-shaped repeated damage zones along a fault trace, (2) long and relatively narrow damage zones, and (3) intensive damage zones in one wall of a fault.

5.1. Wedge-shaped wall damage zones

Some wedge-shaped damage zones are repeated along a

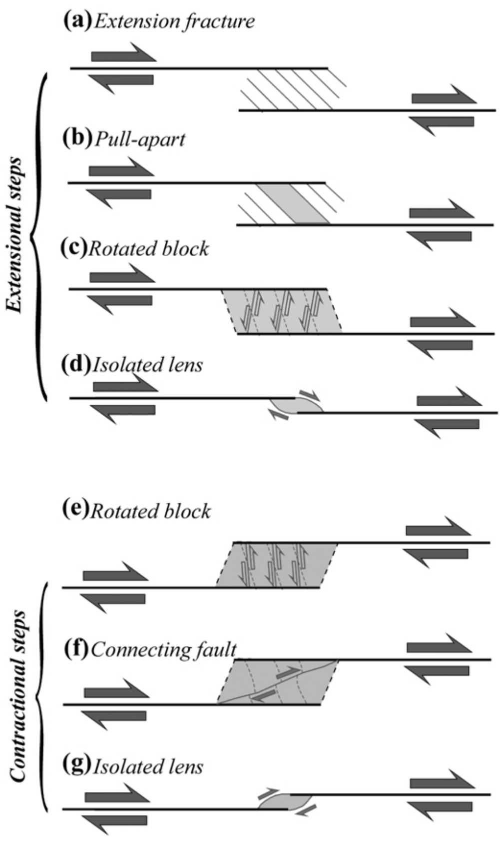

Fig. 6. Schematic illustrations of linking damage zones, the geometries of which depend upon the stress conditions within the fault steps. (a)–(d) Extensional steps, within which extension fractures, pull-aparts, rotated blocks and isolated lenses can be developed. (e)–(g) Contractional steps, within which rotated blocks, connecting faults and isolated lenses can be developed.

fault trace (Fig. 7a), with the size of the wedges generally increasing from the centre to the tips of a fault. These repeated damage zones result from the progressive propagation of a mode II fault tip (Fig. 8a; e.g. Kim et al., 2001a), or perhaps mixed modes II and III (Martel and Boger, 1998). The example shown in Fig. 7a has two central fault segments, each of which has smaller segments at their tips. The build-up of slip and the propagation of these segments would create such repeated wedge-shaped wall damage zones.

There are two possible reasons why wedge-shaped wall damage zones are not frequently observed along the entire length of a fault trace. Firstly, as wedge-shaped tip zones only develop at lateral (mode II) tips, sections that do not pass through the centre of the fault surface will only develop these near the ends of the observed fault trace. Secondly, faults commonly grow through segment linkage (e.g. Segall and Pollard, 1980, 1983; Peacock and Sanderson, 1991, 1994a; Cartwright et al., 1995, 1996; Kim et al., 2000) rather than radially propagating within their own planes (Kim et al., 2001a).

5.2. Long, relatively narrow wall damage zones

Extension fractures or veins in wall damage zones occur in Black Pool, north Devon, UK (Fig. 7b; Beach, 1975), and on Gozo, Maltese islands (Fig. 7c; Kim et al., 2003). This type of wall damage is shown in large-scale in the Lake Basin Fault Zone, Montana, USA (Dobbin and Erdman, 1955; Wilcox et al., 1973; Harding et al., 1985). Fig. 7c and d show wall damage zones that are probably developed at mode III fault tips. This is inferred from the low displacement and lack of through-going fault segments in these examples. Such structures are also described by Pollard et al. (1982) and Younes and Engelder (1999), while Martel and Boger (1998) make the same interpretation of similar structures.

The geometry of this type of damage zone is partly controlled by the angle between the extension fractures (e.g. joints or veins) and the fault. Cox and Scholz (1988b) suggest that extension fractures generally form at ~45° to the master fault, although this angle varies considerably (Martel and Boger, 1998), with the angle depending on the fault type and the stress system (e.g. Peacock and Sanderson, 1995b). Willemse et al. (1997) and Mollema and Antonellini (1999) postulate that extension fractures (that form parallel to the local maximum compressive stress) are the initial fracturing prior to the formation of the master fault (Cox and Scholz, 1988b). This type of fracture occurs in the wall damage zones shown in Figs. 7b–d and 8b and c. Some of the curved fault tips (or wing cracks) and cross-joints may indicate later shearing and rotation around the fault zone.

We interpret the en échelon fractures within long, relatively narrow wall damage zones as primary *antithetic faults* (e.g. Fig. 7e) or as extension fractures that have been reactivated as antithetic faults (e.g. Fig. 7c) because some of the en échelon fractures themselves show wing cracks branching off from their tips (Fig. 7c and e). These wing cracks and the high angle of the en échelon fractures to the master fault indicate that they are antithetic faults (Kim, 2000), which may be reactivated extension fractures (Fig. 7c; McGrath and Davison, 1995). The bisector between the antithetic and master faults at Rame Head is >90° (Fig. 7g).

Synthetic faults (Figs. 7f and 8d) can also occur in the wall damage zone of a master fault (Tchalenko, 1970; Naylor et al., 1986). Damage zones, consisting of a combination of antithetic and synthetic faults near mode III fault tips, generally have symmetric sizes and shapes across a fault trace, although the fracture patterns may not be symmetric (Fig. 7e and f; Kim et al., 2003).

The up- and down-dip tips of a strike-slip fault are mode III tips (Fig. 2). Some long and relatively narrow damage zones in the walls of faults may be the preservation of mode III tip damage zones, left behind as fault propagated through the rock (Figs. 7b–g and 8b–e). The sizes and shapes of mode III damage zones are generally symmetric in map view and cross-section

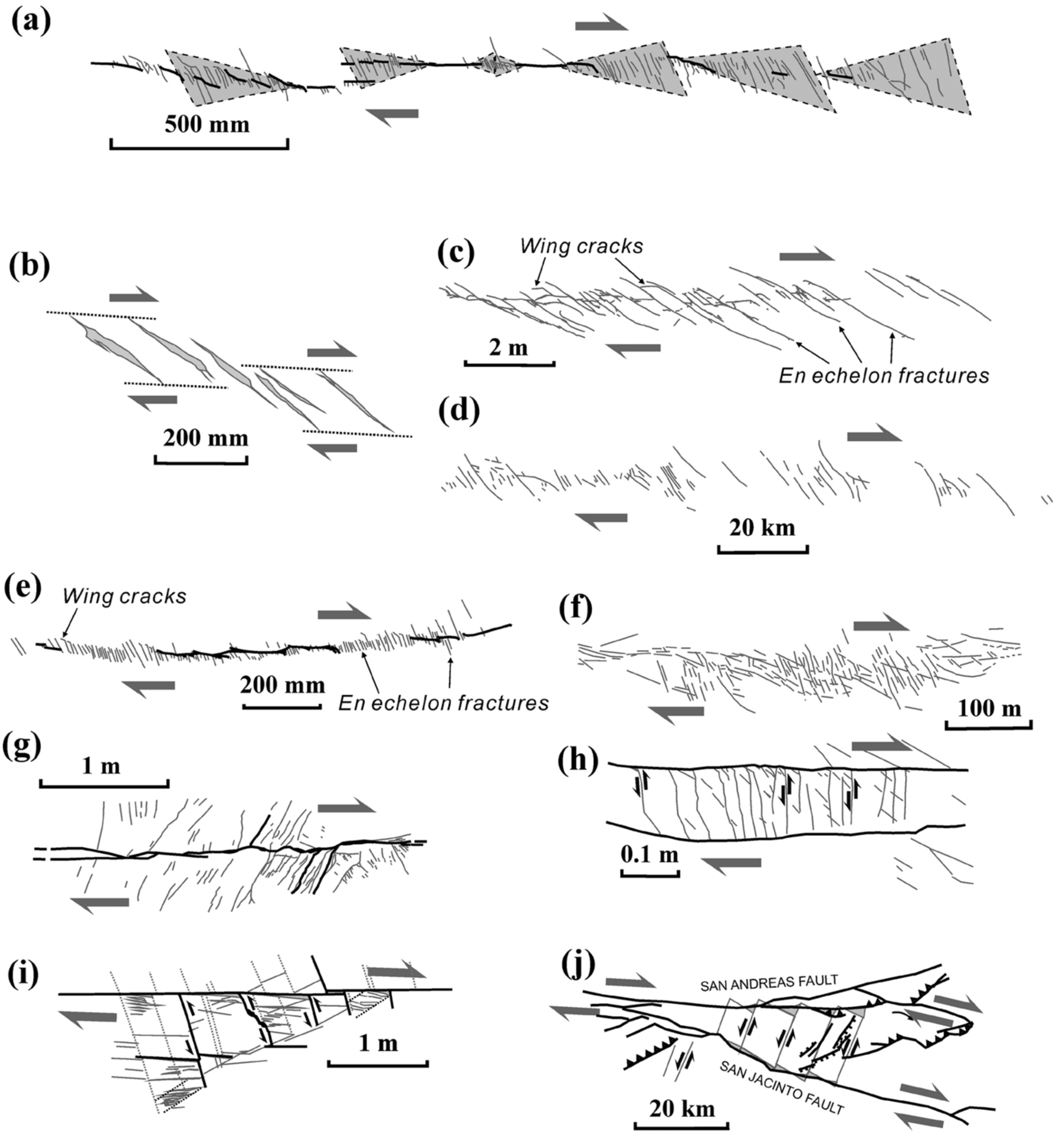

Fig. 7. Examples of wall damage zones around strike-slip faults. (a) Repeated mode II tip damage zones on Gozo, Maltese islands (Kim, 2000). (b) En échelon veins at Black Pool, north Devon, UK (Beach, 1975). (c) Extension fractures around a fault trace on Gozo, Maltese islands (Kim, 2000). (d) Normal faults within the strike-slip Lake Basin Fault Zone, Montana, USA (Dobbin and Erdman, 1955; Wilcox et al., 1973). (e) Antithetic and synthetic faults on Gozo, Maltese islands (Kim, 2000). (f) Antithetic and synthetic faults at Dasht-e Bayaz, Iran (Tchalenko, 1970; Tchalenko and Ambraseys, 1970). (g) Antithetic faults at Rame Head, UK (Kim et al., 2001b). (h) Joint drags at Rush, near Dublin, Ireland (Dewey, 1966). (i) Block rotation and triangular opening at Crackington Haven, UK (Kim, 2000). (j) Block rotation and triangular opening in southern California (Nicholson et al., 1986). Thick line = major fault, thin line = minor fault, shading = vein in small scale examples and basin in large scale examples.

(Kim et al., 2003), indicating that stress perturbations at a mode III fault tip is approximately symmetric across a fault. Note, however, that the structures *within* mode III damage zones are not necessarily symmetrical. Damage zones at the mode II tips tend to be asymmetric, probably because one side of the tip zones is extensional but the other side is contractional (Pollard and Segall, 1987; Martel and Boger, 1998).

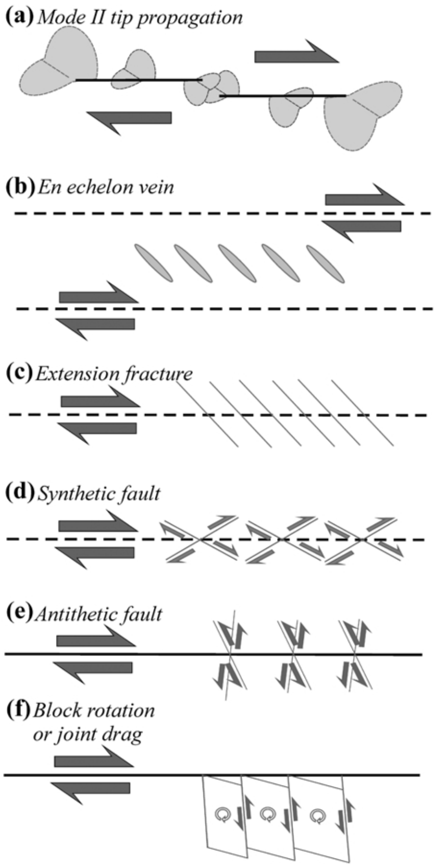

Fig. 8. Schematic illustrations of wall damage zones. (a) Propagation of a mode II fault tip. (b) and (c) Extension fractures in a wall damage zone. (d)–(f) Secondary faults in a wall damage zone. Wall damage zones are produced by propagation of tip damage zones through the rock, or by deformation around the fault as slip increases.

5.3. Wall damage zones that are asymmetric across faults

Intense wall damage zones can result from frictional attrition as slip builds up on a fault. For example, faults with several millimetres to several centimetres slip on Gozo (Kim et al., 2003) have relatively few, low slip fractures in their wall-rocks, whereas Crackington Haven (Kim et al., 2000) and Rame Head (Kim et al., 2001b) have relatively larger slip (several tens of centimetres to several metres), and show more intensive wall damage zone structures.

Block rotation (Figs. 7h–j and 8f) commonly occurs around large slip faults (e.g. Dibblee, 1977). Small-scale block rotation is typically associated with triangular openings at the intersections between faults (Kim et al., 2000). Antithetic faults develop almost normal to the master fault, and the blocks rotate synthetically with respect to the master fault (Figs. 7h–j and 8f). Antithetically rotated blocks can be developed if a fault zone contracts across its thickness (Martel et al., 1988; Gross et al., 1997). *Joint drags* (Fig. 7h; Dewey, 1966) can also be an example of this type of damage zone. Similar types of rotated blocks are also observed between sub-parallel faults (e.g. Nicholson et al., 1986; Ron et al., 1986; McGrath and Davison, 1995; Watterson et al., 1998) and in fault steps (Terres and Sylvester, 1981).

6. Model for damage zones around strike-slip faults

This section presents a model for damage zones around the tip line of strike-slip faults, i.e. the mode II, mode III and mixed-mode tips. This is a three-dimensional interpretation based on the two-dimensional observations presented in the previous sections. Fig. 9 shows the range of damage zone styles that are commonly found around strike-slip fault zones, based on observations presented in Figs. 3–8. The distributed areas of damage zones around a linked strike-slip fault are also illustrated in Fig. 10, based on observed damage zones. Slip at the mode II tips of a strike-slip fault is commonly mainly accommodated by extension fractures (Fig. 9), with dilation at one side of a fault tip and contraction at the other side (e.g. Pollard and Segall, 1987). Ahead of a fault tip, the stress perturbations commonly form wedge-shaped damage zones with antithetic faults (Figs. 9 and 10b). In contrast, slip at the mode III tips of a strike-slip fault appears to generate symmetric stress perturbations (e.g. Pollard and Segall, 1987), with synthetic and antithetic fractures accommodating slip commonly approximately symmetrically distributed across the fault (Fig. 10a). At a cross-sectional view of a strike-slip fault, mode III fault tips generally show symmetric cone-shaped (convex downwards) stress perturbations, and the fracture pattern resembles bifurcating flower structures (McGrath and Davison, 1995; Kim et al., 2003).

Secondary faults and fractures around faults can be related to tip modes and/or locations around the fault. For example, McGrath and Davison (1995) argue that the observed variation of damage zone geometries in strike-slip faults are caused mainly by different stress regimes, i.e. transpression, transtension and simple shear. Martel and Boger (1998) also argue that secondary fractures depend on location around the strike-slip fault tip line. The simple models presented by McGrath and Davison (1995) and Martel and Boger (1998) cannot explain the wide variety of damage zones observed around strike-slip faults. The models presented in Figs. 9 and 10 are an attempt to explain the complexity of damage zones that can develop around strike-slip faults (Figs. 1 and 3–9), based on observations from the studied areas and published examples.

Based on the examples presented in this paper, we argue that the patterns of damage zones depend on three-dimensional locations around the fault, and stress perturbations that are controlled by tip mode, amount of slip, and interaction between segment faults. Different patterns of damage zones at the same tip mode may result from variations in confining pressure (Petit and Barquins, 1988; McGrath and Davison, 1995), orientation of the maximum compressive stress (Segall and Pollard, 1983), fault

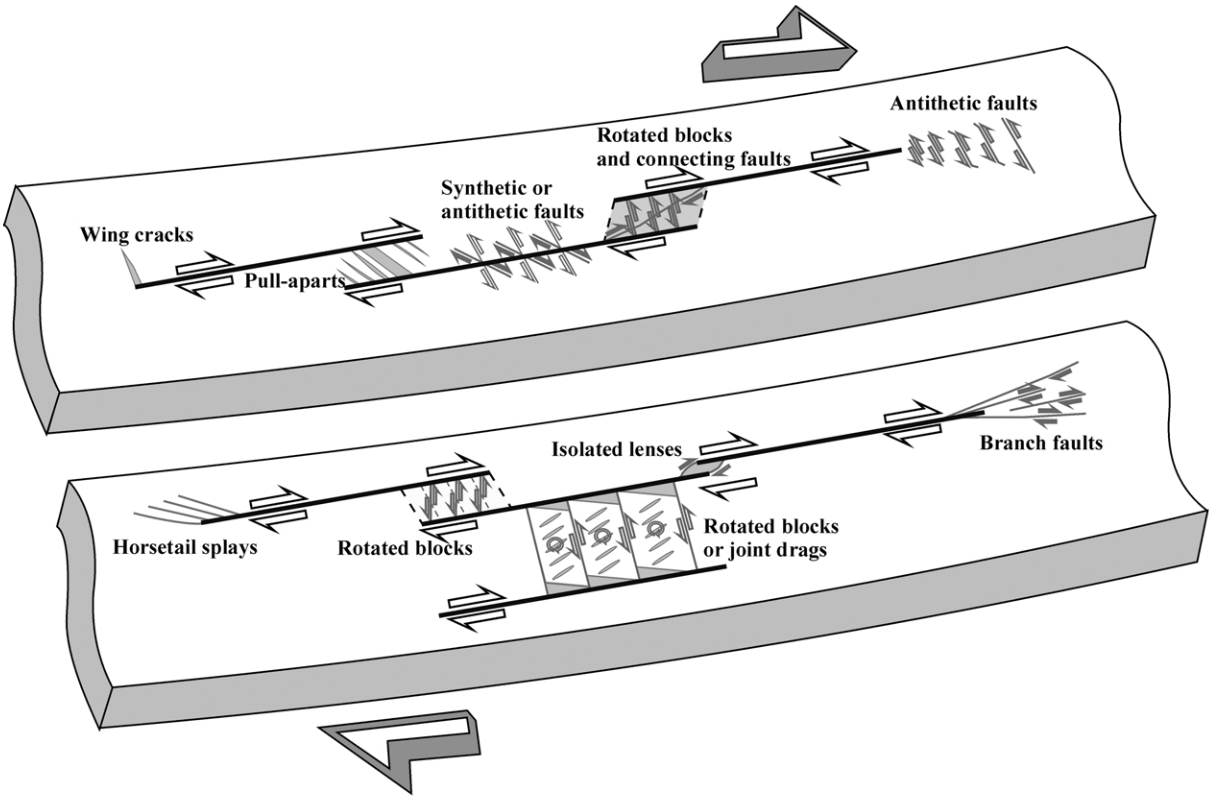

Fig. 9. Schematic diagram showing structures that typically occur in damage zones around strike-slip faults. These structures include connecting faults, branch faults, wing cracks, pull-aparts, synthetic or antithetic faults, horsetail fractures, rotated blocks or joint drags, and isolated lenses.

propagation direction, and from variations in fault evolutionary stage (Kim, 2000). We acknowledge that other factors are also likely to influence the nature of damage zones, including lithology, fluid pressure and temperature, and that no simple model will describe all of the complexity in the deformation that occurs around faults. The models presented in Figs. 9 and 10 do, however, emphasize how damage zones are likely to vary around a fault tip line.

Damage zone patterns tend to become more complex during the evolution of damage zones (Kim et al., 2003). Tip damage zones are developed as a fault initiates and propagates through the rock (Figs. 3 and 4). A propagating fault is likely to eventually interact with adjacent fault segments as its length and slip increase, creating a linking damage zone. A variety of damage zones can be produced depending on the stress state within the fault step (Figs. 5 and 6). Increasing slip on the interacting fault segments will cause them to link into a composite fault zone (e.g. Peacock,

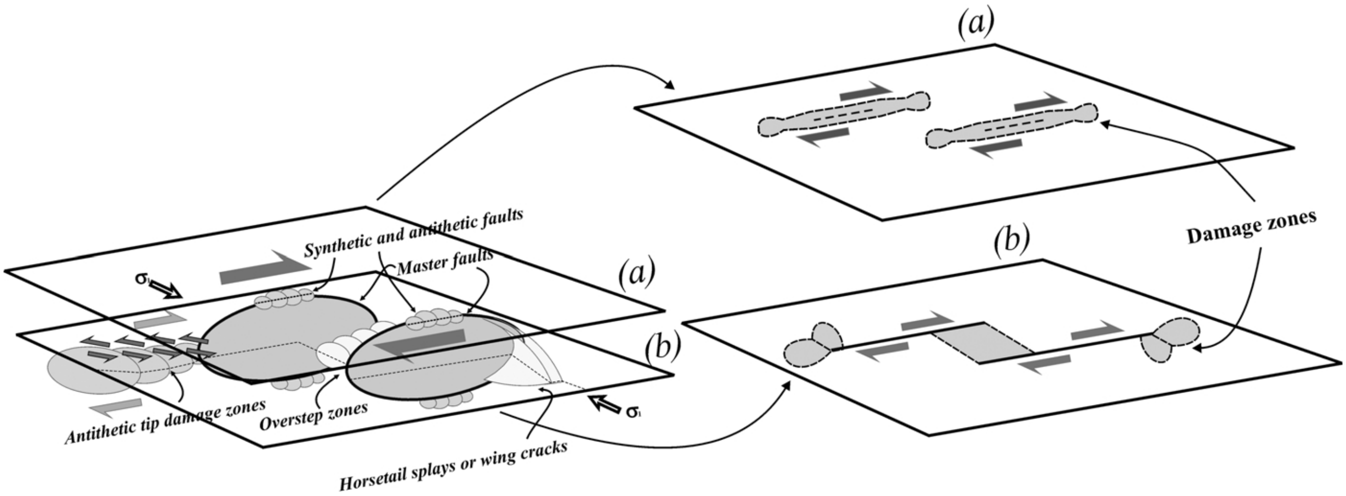

Fig. 10. A conceptual three-dimensional model of the distribution of damage zones around a strike-slip fault, showing characteristic fractures at mode II and III fault tips and at fault steps. The mode III tip damage zone (a) is typically symmetrical, while the mode II tip damage zone (b) is typically asymmetric.

1991; Peacock and Sanderson, 1991; Cartwright et al., 1995). Increased slip on the composite fault zone can add to the damage already created by the initiation, propagation, interaction and linkage of the fault segments (Figs. 7 and 8). Complex finite strains are therefore possible in damage zones, especially if there is a complex reactivation history (e.g. Kim et al., 2001a).

7. Damage zones around normal, reverse and thrust faults

The classification scheme developed for strike-slip faults can be extended to other fault types. The damage zones presented in Fig. 11 are from normal faults in the Liassic limestones and mudrocks of the Somerset coast (e.g. Peacock and Sanderson, 1991, 1994a, 1999), and from the Cretaceous Chalk of Flamborough Head, Yorkshire (Peacock and Sanderson, 1994b; Peacock and Zhang, 1994). They illustrate how damage zones around normal faults can also be divided into tip-, wall and linking-damage zones. The details of the structures developed within damage zones may be different, but the overall pattern and development is similar to those presented for strike-slip faults in Figs. 9 and 10. Pull-aparts characterise extensional steps (Fig. 11b) whereas antithetic faults characterise contractional steps (Fig. 11c). The type of damage zone shown in Fig. 11d is not illustrated for strike-slip faults (Figs. 1–10), it being a *relay ramp* produced by interaction between normal faults in map view (e.g. Larsen, 1988). This involves interaction between faults at their mode III tips, in an area termed a *neutral relay* by Walsh et al. (1999).

The damage zones presented in Fig. 12 are from thrust faults, and illustrate how damage zones around thrust faults can also be divided into tip damage zone (Fig. 12a and b), linking damage zone (Fig. 12c and d) and wall damage zone (Fig. 12e). Tip damage zones around thrust faults commonly contain fold axial surfaces that intersect the fault at the tip (e.g. McConnell et al., 1997; Nicol et al., 2002). Synthetic faults, antithetic faults and horsetail fractures are also observed (Fig. 12), as in strike-slip and normal fault systems. Although Walsh et al. (1999) show that contractional, extensional and neutral relay steps can occur along thrusts, extensional steps appear to be rare. This is probably because thrust faults tend to step up the stratigraphic section (Aydin, 1988), commonly in a staircase trajectory (e.g. Boyer and Elliott, 1982). Thrust fault slip is commonly distributed on splays and back thrusts, with bedding plane slip, minor folding, cataclastic flow and bed thickness variations all commonly occurring (McConnell et al., 1997). Although the details of the structures developed within the damage zones of thrust

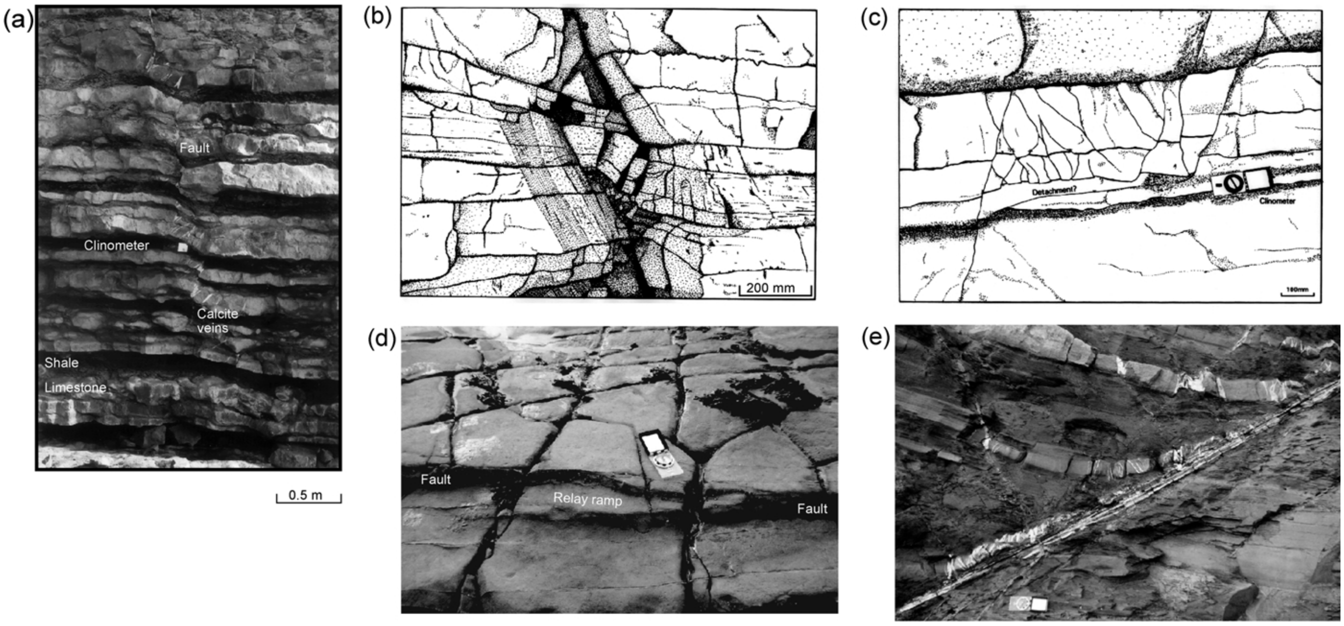

Fig. 11. Damage zones around normal faults. (a) Tip damage zone developed at the downward tip of a normal fault in the Liassic limestones and mudrocks of the south Wales coast, with damage consisting of bed rotation and veins. (b) Linking damage zone in an extensional step in the Cretaceous Chalk at Flamborough Head (Peacock and Zhang, 1994). Damage zone structures include rotation of beds, brecciation and voids. (c) Linking damage zone in a contractional step in the Chalk at Flamborough Head. Damage zone structures include a network of synthetic and antithetic faults, with some thinning of beds. (d) Relay ramp between normal faults that step in map view, on a bedding plane of Liassic limestone, East Quantoxhead, Somerset (Peacock and Sanderson, 1994a). (e) Wall damage zone along a normal fault with ~20 m slip, at Kilve, Somerset. Damage includes synthetic and antithetic faults, veins and drag of beds.

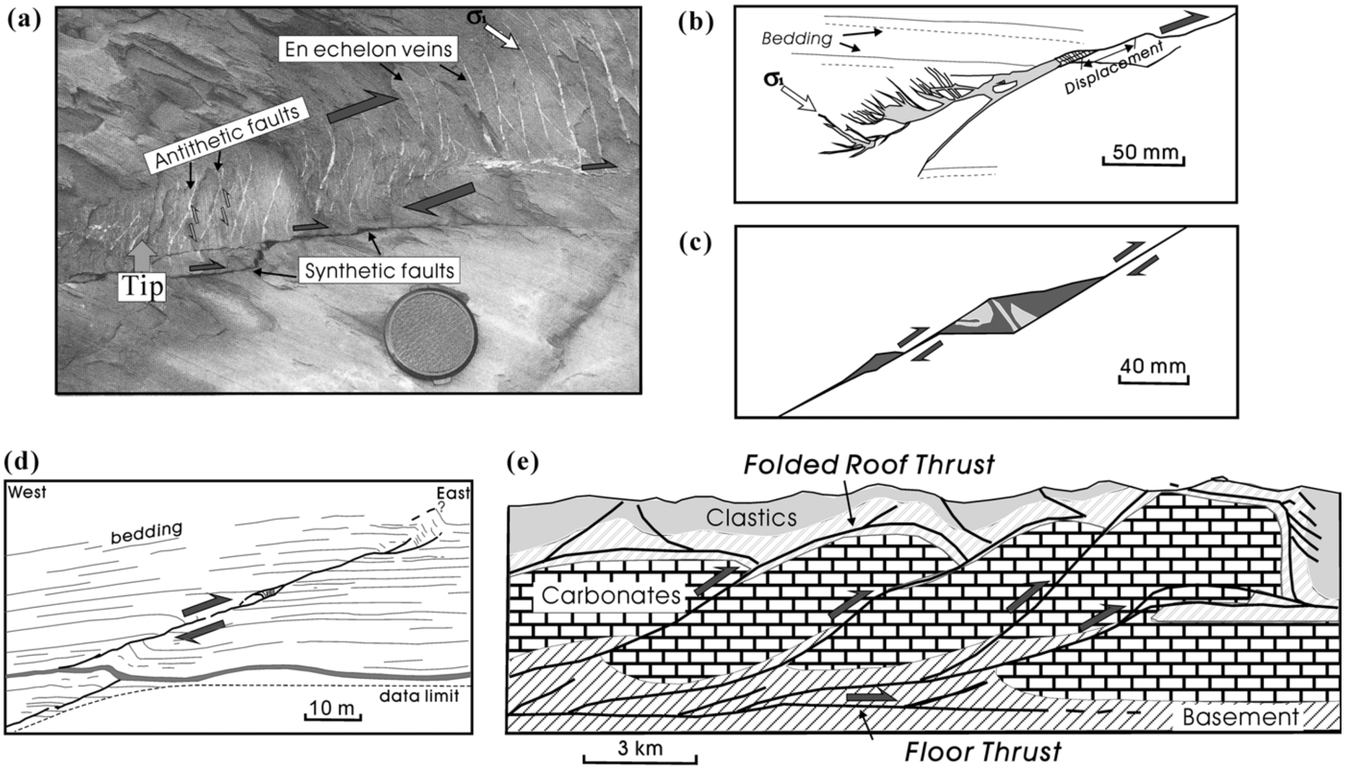

Fig. 12. Damage zones around reverse and thrust faults. (a) Tip damage zone in the Lower Jurassic limestones and shales at Kilve, Somerset, UK (McGrath and Davison, 1995). The damage zone includes folds, en échelon veins, synthetic faults and antithetic faults. (b) Tip damage zone at Kilve, showing horsetail fractures (McGrath and Davison, 1995). (c) Linking damage zone showing pull-aparts in an extensional step in the Cretaceous Urganian limestone near Lake Sanetsch, Switzerland (Aydin, 1988). (d) Linking damage zone showing folds and an isolated lens in a contractional step in the Carboniferous limestone and marl beds at Black Rock Quarry, south Wales (Nicol et al., 2002). (e) Wall damage zone showing complex duplexes and splays, in the central Appalachian Valley and Ridge (e.g. Perry, 1978; Boyer and Elliott, 1982).

faults are different from those in strike-slip faults, the overall pattern and evolution appears to be very similar to those presented in Figs. 9 and 10.

8. Conclusions

Fault damage zones show a wide variety of geometries and fracture patterns. They can be divided into three main zones based on their locations:

- *Tip damage zones* can be sub-divided on the basis of the slip mode at the fault tip, and by fracture patterns within damage zones, which themselves are mainly controlled by the slip modes at the fault tips. For example, wing cracks, horsetail fractures, antithetic faults, and synthetic faults can all occur at mode II fault tips. Tip damage zone are typically asymmetric at mode II tips, reflecting extensional and contractional zones across a fault trace. In contrast, damage zones are generally symmetrical at mode III tips, with synthetic and antithetic faults accommodating slip along the mode III fault tip.
- *Linking damage zones* are developed between two sub-parallel, non-coplanar fault segments. The geometry of, and structures within, these damage zones are strongly controlled by whether the steps are extensional or contractional. Extension fractures and pull-aparts typically form at extensional steps, whereas connecting faults develop in contractional steps. Rotated blocks, isolated lenses and strike-slip duplexes can occur in both types of fault step.
- *Wall damage zones* may result from the propagation of mode II and III tips through the rock, or from damage produced by the build-up of slip on a fault. Damage zone structures include en échelon extension fractures, antithetic faults, synthetic faults, and rotated blocks with associated triangular openings.

Damage zones around small- and large-scale strike-slip, normal and thrust faults fit well into this classification scheme. Physical models for fault growth must address the complexity caused by faults not growing by simple propagation within a plane, but forming by a more complicated breakdown process (Scholz, 1968; Cox and Scholz, 1988a,b; Lockner et al., 1991; Vermilye and Scholz, 1998, 1999). Complexity is likely to exist in fault zones, especially around faults that have been reactivated with different slip senses (Kim et al., 2001a). The classification scheme presented here does, however, characterise the main types of damage zones.

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