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Active relay ramps and normal fault propagation on Kilauea Volcano, Hawaii

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Abstract

Individual segments of the Koae Fault System, Hawaii, show four patterns of structures around fault tips, and these are inferred to represent four evolutionary stages of fault growth. These are: (1) monoclinal bending occurs, probably above a steeply dipping fault at depth, (2) cracks develop in the hinges of the monocline, (3) throw starts to develop on the cracks when they reach a width of about 3 m, which is probably when they link downwards to the normal fault, and (4) rollover and related cracks develops in the hanging wall as throw increases. Widths of monocline- and fault-related cracks obey a power-law distribution, with a 3 m upper cut-off, beyond which the monocline- and fault-related cracks develop a throw and become faults. Relay ramps are common within the highly segmented Koae and Hilina active normal fault systems. Three distinct geometries of relay ramps can be identified at Kilauea Volcano, and these are inferred to represent the following three evolutionary stages of relay ramps. (1) Where the bounding faults understep, the relay ramps have a gentle dip, and a set of en échelon cracks may cut across the relay ramp; these cracks suggest that the two understepping faults connect into a single fault at depth. (2) The dip of the relay ramp increases as the faults overstep. Connecting faults start to cut across the relay ramp. (3) When the relay ramp is breached by the connecting fault, a single, irregular fault is produced. Cracks or small breaching faults across a relay ramp suggest the bounding faults are connected at depth, and suggest that the bounding faults may both slip during an earthquake event. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Relay ramps; Normal fault propagation; Monocline

1. Introduction

The aims of this paper are to document examples of relay ramps in active fault zones and to illustrate the importance of fault propagation, interaction and linkage in active normal fault systems. The geometry of faults and relay ramps exposed at the surface are used to infer their three-dimensional geometries at depth. A model of fault evolution is proposed based on the inferred three-dimensional geometry. Simple analogue modelling is used to show different styles of linkage between faults that are connected or not connected at depth. The Koae and Hilina fault systems on Kilauea Volcano, Hawaii, were chosen for this analysis because they have excellent exposure, and there is an extensive record of seismic and rupture activity (e.g. Ando, 1979; Denlinger and Okubo, 1995; Gillard et al., 1996).

1.1. Definition and geometry of relay ramps

A relay ramp (Fig. 1) is a volume of rotation between two normal fault segments that overstep along strike and that have the same dip direction (Goguel, 1952; Larsen, 1988). Macdonald (1957) calls these structures monoclinal ramps. Peacock et al. (2000) give other synonymous terms. Relay ramps are very common in normal fault systems, and they can be important foci for hydrocarbon migration (Larsen, 1988; Morley et al., 1990; Peacock and Sanderson, 1994, their fig. 16). A relay ramp connects the footwall with the hanging wall of a fault system, and transfers displacement between the overstepping segments (Peacock and Sanderson, 1991, 1994). Displacement transfer by relay ramps is accompanied by steep displacement gradients along fault segments at oversteps. Relay ramps typically contribute to a local minimum in total fault displacement at a linkage point (Peacock and Sanderson, 1991, 1994; Schlische, 1992). Networks of faults can occur in a relay ramp to accommodate the dipping of beds (e.g. Griffiths, 1980).

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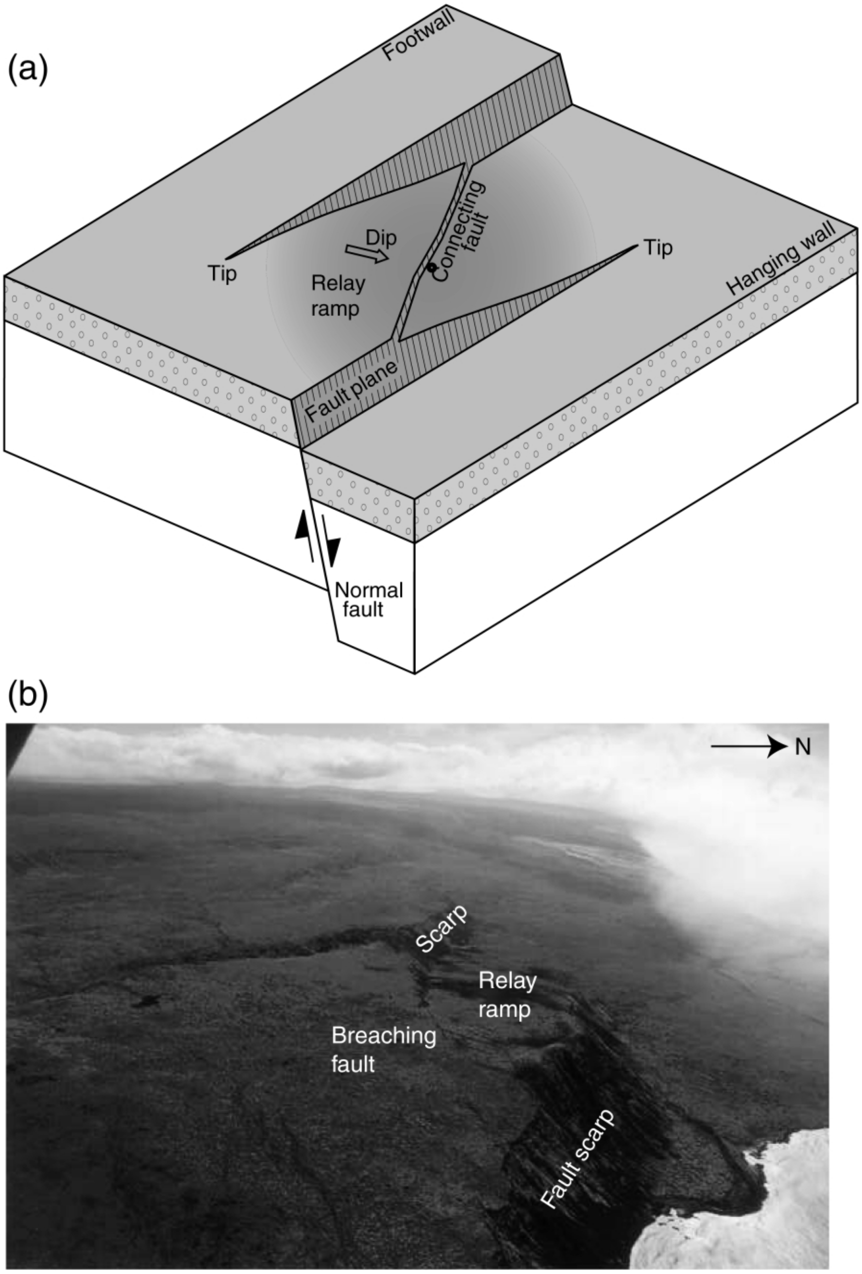


Fig. 1. (a) Block diagram of a relay ramp between two normal faults that overstep in map view and that dip in the same direction (e.g. Goguel, 1952; Larsen, 1988; Peacock et al., 2000). Tilting of rocks within the relay ramp transfers displacement between the faults. The faults that bound the relay ramp become connected by a breaching fault. On Kilauea Volcano, breaching faults commonly cut across the centre of the relay ramp. (b) Oblique air photograph taken from a height of about 1000 m, looking east along the Hilina Fault System. The Hilina Fault System is an active set of normal faults related to southward-slippage of the flank of Kilauea Volcano into the sea. A relay ramp occurs between the overstepping fault segments, with a zone of smaller synthetic breaching faults.

1.2. Previous work on active relay ramps

Descriptions of active relay ramps from other regions include the Basin and Range Province, western USA (e.g. Crone and Haller, 1991; dePolo et al., 1991; Machette et al., 1991; Dawers and Anders, 1995), the East African Rift (Griffiths, 1980; Morley et al., 1990), and Greece (Jackson et al., 1982; Roberts and Jackson, 1991; Stewart and Hancock, 1991). Morley et al. (1990) and Gawthorpe and Hurst (1993) give descriptions of active relay ramps from various other locations around the world. Active relay ramps can control a wide variety of structural processes, including slip and finite displacement patterns (e.g. Zhang et al., 1991; Anders and Schlische, 1994; Dawers and Anders, 1995), rupture patterns and sequences (Crone and Haller, 1991; dePolo et al., 1991; Zhang et al., 1991; Gupta and Scholz, 2000), and basin development (Anders and Schlische, 1994). Active relay ramps can also control other geological processes, including topography, erosion and drainage (Morley et al., 1990; Roberts and Jackson,

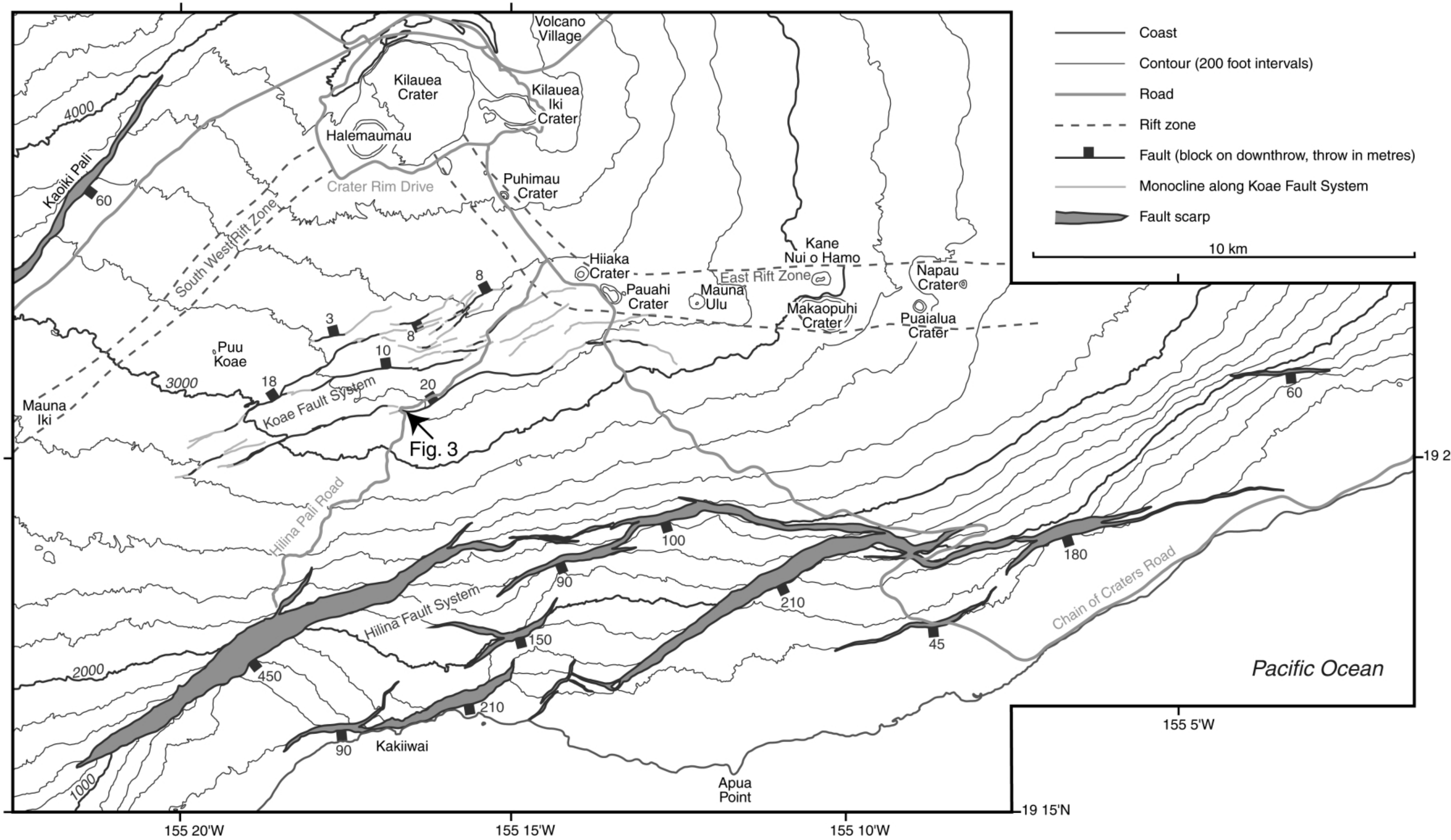
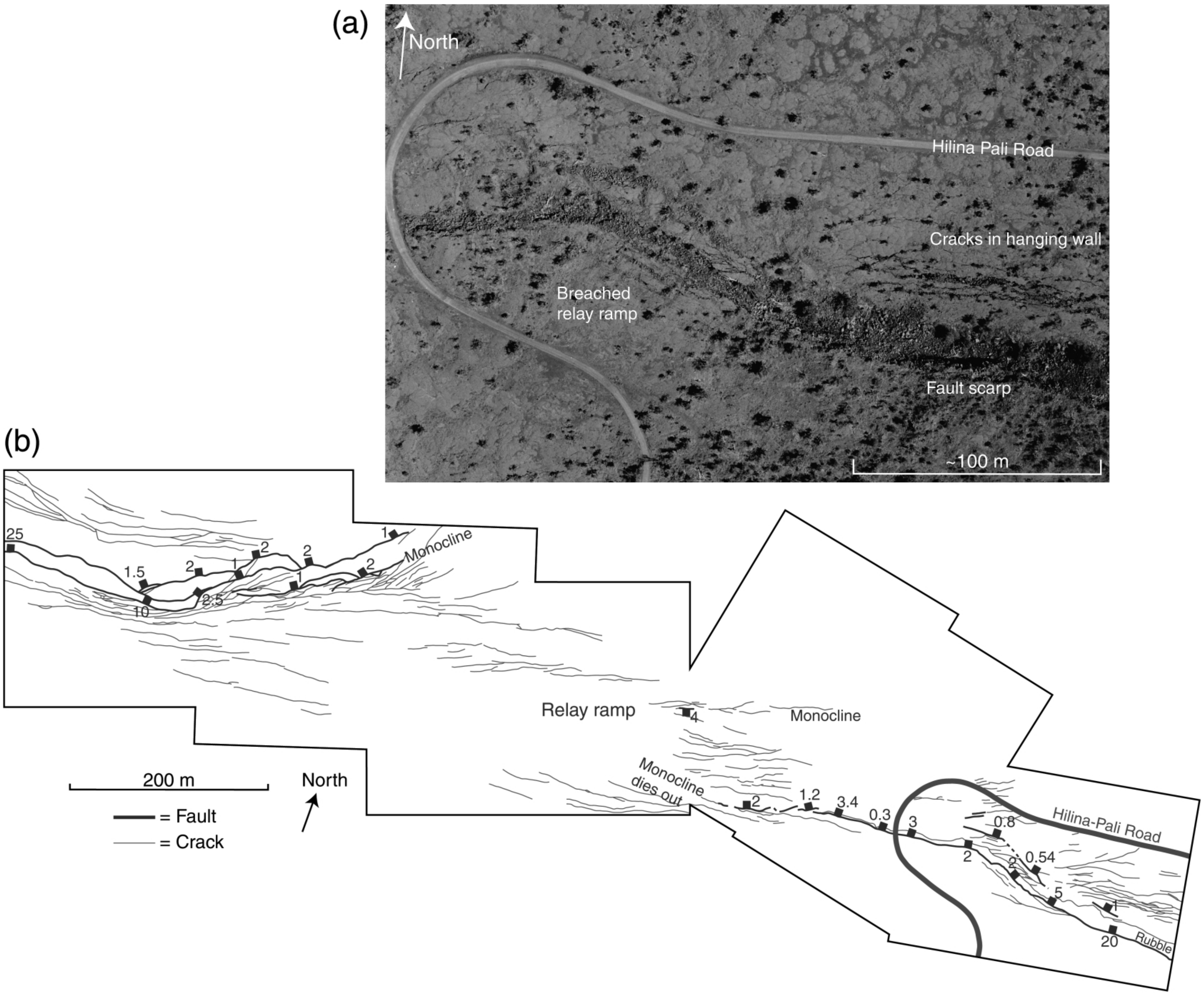


Fig. 2. Map of the southeast part of the Big Island, Hawaii, showing the location of Kilauea Volcano, its rift zones, and its fault systems. This map is based on the USGS 1:24,000 scale maps and photo-quadrangles.


(a)
North
Hilina Pali Road
Cracks in hanging wall
Breached relay ramp
Fault scarp
~100 m
(b)
25
1.5
10
2
2.5
1
2
1
2
2
1
Monocline
Relay ramp
4
Monocline
Monocline dies out
2
1.2
3.4
0.3
3
0.8
Hilina-Pali Road
2
2
0.54
5
1
20
Rubble
200 m
North
= Fault
= Crack

1991; Gawthorpe and Hurst, 1993; Leeder and Jackson, 1993; Jackson and Leeder, 1994), stratigraphy (Gawthorpe and Hurst, 1993), outcrop patterns (Wu and Bruhn, 1994), and the location of volcanic activity (Acocella et al., 1999).

There have been several accounts of minor faults within active relay ramps. Griffiths (1980) describes complex systems of 'box faults' within relay ramps in the East African Rift. Jackson et al. (1982, their figs. 6 and 7) show ground ruptures within a relay ramp at Kaparelli, Greece. Crider and Pollard (1998, their fig. 4) describe the small faults and fractures that have developed in a relay ramp in basalt in Oregon. Acocella et al. (2000, their fig. 3) show photographs of relay ramps between active normal faults in Iceland. Ferrill et al. (1999) describe the 'corrugation' of large faults in the Basin and Range Province resulting from the linkage of small fault segments, with connection either by curving of fault tips (tip to plane) or by connecting faults. They use earthquake data to speculate on the three-dimensional geometry and connection of overstepping faults at depth, suggesting that the largest earthquakes occur on fault segments that are connected at depth.

In spite of these accounts of active relay ramps, there has been limited work published on how relay ramps at the Earth's surface may evolve, or about the implications for the three-dimensional geometries of the active faults. Trudgill and Cartwright (1994) describe intense fracturing at fault tips in Canyonlands National Park, Utah, with relay ramps breached by faults nearly perpendicular to the main faults. They illustrate the 3D geometries of these relay ramps, but the faults detach into a salt layer tens of metres beneath the Earth's surface.

1.3. Structural geology of Kilauea Volcano

Kilauea Volcano (latitude 19°23′N, longitude 155°18′W) is an active basaltic shield volcano. Eruptive activity is concentrated in its summit caldera and along two rift zones, the East Rift Zone and the South West Rift Zone. The south flank of the volcano is mobile, slipping seawards at rates of about 100 mm per year (Owen et al., 1995). The south flank contains two prominent normal fault systems, the Koae and Hilina fault systems (Fig. 2). The fault systems are excellently exposed because of the limited rainfall and erosion, and the sparse vegetation.

The Koae Fault System is a zone of normal faulting about 2 km wide perpendicular to strike, extending from the East Rift Zone towards the South West Rift Zone (Fig. 2). It has a dominant downthrow to the north, with individual fault segments having a throw of up to about 20 m. The Koae Fault System represents about 25 m of crustal extension since the last re-surfacing event (Duffield, 1975), 400–750 years ago (Holcomb, 1987; Wolfe and Morris, 1996). Several recent episodes of ground cracking and seismic activity in the Koae Fault System have been related to intrusion of magma from the rift zones (Kinoshita, 1967; Klein et al., 1987), suggesting that some activity in the Koae Fault System is related to magmatic activity. Earthquake hypocentres have depths of 1–4 km (Klein et al., 1987), suggesting that the faults originate and have greater displacements at depth (Parfitt and Peacock, 2001). The Koae Faults would especially have greater displacements at depth if they were growth faults periodically covered by lava, because an approximately flat ground surface is produced by each resurfacing event. Explanations for the origin of the Koae Fault System include that it is a 'tear-away' zone related to extension of the East Rift Zone (Duffield, 1975; Swanson et al., 1976), or that it accommodates footwall uplift north of the Hilina Fault System (Parfitt and Peacock, 2001).

The Hilina Fault System forms a south-facing scarp up to 500 m high, and is related to seaward slippage of the south flank of Kilauea Volcano. Denlinger and Okubo (1995) show that there was up to 10 m seaward movement of the South Flank between 1970 and 1989. A magnitude 7.2 earthquake occurred on the basal thrust beneath the southern part of Kilauea Volcano in November 1975, and related slip occurred on the Hilina Fault System (Lipman et al., 1985). Movement occurred on several segments of the Hilina Fault System over a length of about 25 km, with up to 1.5 m throw at the surface. The Hilina Fault System has been interpreted as either a shallow, listric gravitational slump structure (Swanson et al., 1976; Ando, 1979; Wyss et al., 1981; Gillard et al., 1996; Morgan et al., 2000) or as being approximately planar and deep, connecting down to the basal thrust at about 9 km depth (e.g. Lipman et al., 1985; Got et al., 1994; Parfitt and Peacock, 2001).

The fieldwork presented in this paper improves on previous work on the Koae and Hilina fault systems. Macdonald (1957) shows a simple figure and gives a brief description of 'monoclinal ramps'. Duffield (1975) gives a more detailed description of the Koae Fault System and mentions the relay ramps. Various models for deformation of Kilauea Volcano incorporate the faults, but these tend to be based on geophysical or geodetic data rather than on detailed fieldwork (e.g. Got et al., 1994; Morgan et al., 2000).

2. Fault propagation in the Koae Fault System

2.1. Mapping within the Koae Fault System

Mapping of part of the Koae Fault System (Fig. 3) was

Fig. 3. (a) Vertical air photograph taken from a height of about 300 m showing part of the Koae Fault System. The Hilina–Pali road loops around as it passes over the fault scarp. This photograph is part of a set used as a base to map a relay ramp (see part (b)). (b) Map of part of the Koae Fault System. Ticks are shown on the down-thrown sides of faults, with throws in metres. All of the cracks and faults shown appear to be dilated cooling joints (Peacock, 2001). A relay ramp about 200 m wide occurs between the two understepping fault zones.

Fig. 4. Photograph of a polygonal cooling joint that has opened up obliquely as an irregular, approximately E–W striking crack adjacent to the Koae fault system (see Peacock, 2001). Even though the joints and faults are approximately straight at the scale of the map in Fig. 3, they are more irregular when observed in detail.

carried out using air photographs taken from heights of about 300 m (Fig. 3a). Mapping involved the measurement of fault throws and dips, and widths of cracks (which are opening-mode fractures). Several problems were encountered while mapping the Koae Fault System. It is difficult to accurately measure throw on the largest faults because they commonly have rubble-filled cracks at the foot of their scarps. The faults appear to be vertical, but fracturing and weathering make it difficult to identify fault surfaces. Although no slip indicators are observable along the faults, normal faulting is indicated by the opening-mode displacements of the fault-related cracks (e.g. Peacock, 2001) and by earthquake solutions (e.g. Klein et al., 1987). The faults cut an irregular topography, so measurement of gentle ground surface slopes may have little structural significance. Some fault-related cracks (i.e. cracks adjacent and sub-parallel to the faults) are too narrow and closely spaced to map, even at this scale. Also, it can be difficult to distinguish fault-related cracks from cooling joints that were opened-up as the crust of solid basalt was wrinkled during flow of the underlying lava. Fault-related cracks are also probably opened-up cooling joints (Fig. 4; Peacock, 2001); they tend to be longer, straighter, more regular in width and orientation, and sub-parallel to the faults. Cracks related to opened-up of cooling joints during flow of underlying lava are shorter, less regular and with a wider range of orientations because the dilation related to lava flow is more localised than that related to faulting.

2.2. The initiation and propagation of the Koae Faults at the Earth's surface

To determine how individual fault segments propagate, we looked at the areas around the fault tips. Four structural relationships occur from beyond the fault tips to where the faults have metres of throw. These are inferred to represent four stages in the propagation of the faults (Fig. 5). Duffield (1975, his fig. 4) shows a similar sequence in a series of photographs, from en échelon fractures, to the breakage of a monocline, to the development of a fault scarp.

Stage 1 involves the Koae faults dying out into monoclines, usually about 15 m wide and with an amplitude of about 3 m (Fig. 6; also see fig. 4(a) of Duffield (1975). It is possible that a monocline represents drag beyond the lateral tip of a normal fault (e.g. Walsh and Watterson, 1987, their fig. 7). It is probable, however, that a monocline represents deformation above the buried lateral continuation of the fault. Stage 2 involves the development of sub-vertical cracks at the monocline boundaries. The cracks develop as fold amplitude increases (Fig. 6; also see Duffield, 1975, his fig. 4b), especially in the monocline hinge towards the footwall of the faults, which shows outer arc extension at the Earth's surface. Stage 3 involves the development of throw on one of the cracks to form a fault. This probably occurs as the cracks link downward into the normal fault. At this stage, the widest, longest cracks usually occur about 15 m apart in the two hinges of the monocline. Some faults have throw on the crack in the hinge nearest the hanging wall with heave (opening) on the crack in the hinge nearest the footwall. Other faults have throw on the crack in the hinge nearest the footwall, e.g. the fault nearest the Hilina–Pali Road (Fig. 3a; also see Macdonald, 1957, his fig. 1). The cracks with heave are typically partly filled by rubble. In places, the ground surface dips steeply (more than 60°) in the monocline, especially where the monocline is breached by the normal fault and a large throw has built up. Such

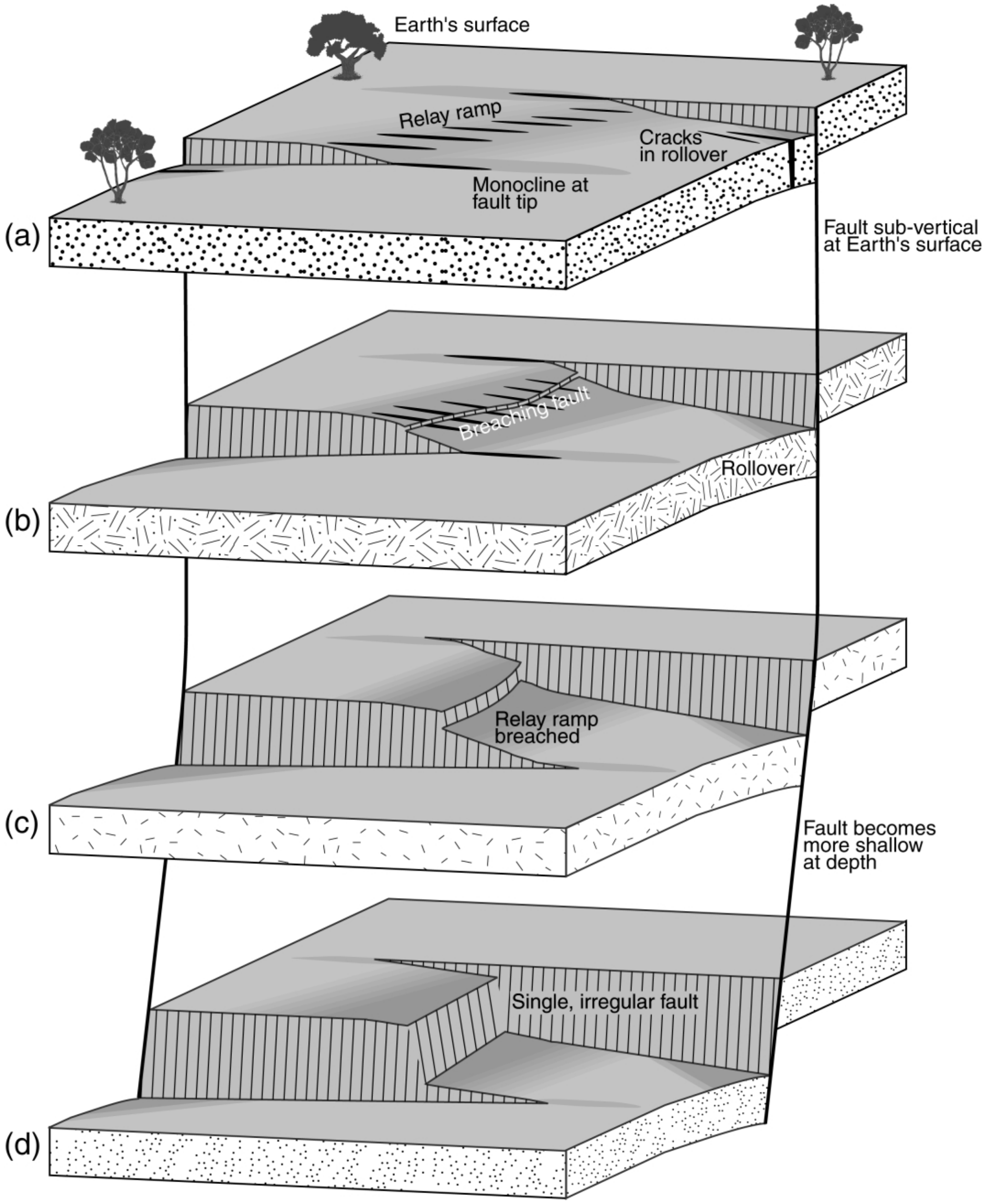


Fig. 5. Block diagrams showing the temporal and spatial evolution of faults in the Koae and Hilina fault systems. Three distinct stages of relay ramps may be identified. (a) The bounding faults understep but may be connected by en échelon cracks. (b) The relay ramp develops as the faults overstep and become connected by a breaching fault as displacement increases. The breaching fault cuts across the centre of the relay ramp (cf. three-dimensional model for ancient exhumed relay ramps; Peacock and Sanderson, 1994, their fig. 12). (c) The relay ramp is breached. The layer in (d) shows a single, irregular fault. Four stages may be identified in the propagation of individual fault segments. (1) A monocline develops above a dipping normal fault (the sub-surface lateral continuation of a fault seen at the surface). (2) Vertical cracks occur bounding and within the monocline, especially in the outer arc (the footwall side). (3) Where the monocline has an amplitude of more than about 3 m, throw typically develops on one or more of the cracks. These cracks probably link downwards into the normal fault. (4) Hanging wall rollover develops as throw increases to ~10 m, probably because the normal fault curves from sub-vertical cracks at the Earth's surface to less steep at depth. Rollover is partly accommodated by cracks in the hanging wall. (Also see Duffield, 1975, his fig. 4.)

steep dips of the ground surface may be partly caused by drape folding and normal drag along the fault, with dilation occurring (e.g. Withjack and Callaway, 2000). Stage 4 involves the development of hanging wall rollover, with folding of the ground surface up to tens of metres from the fault zone. Rollover is probably caused by the normal fault dipping at depth but linking to sub-vertical cracks at the Earth's surface. Rollover is partly accommodated by cracks in the hanging wall (Fig. 3b).

2.3. Fault-related cracks

Field observations and measurements suggest that fault-related cracks in the area of the Koae Fault System (Fig. 3b)

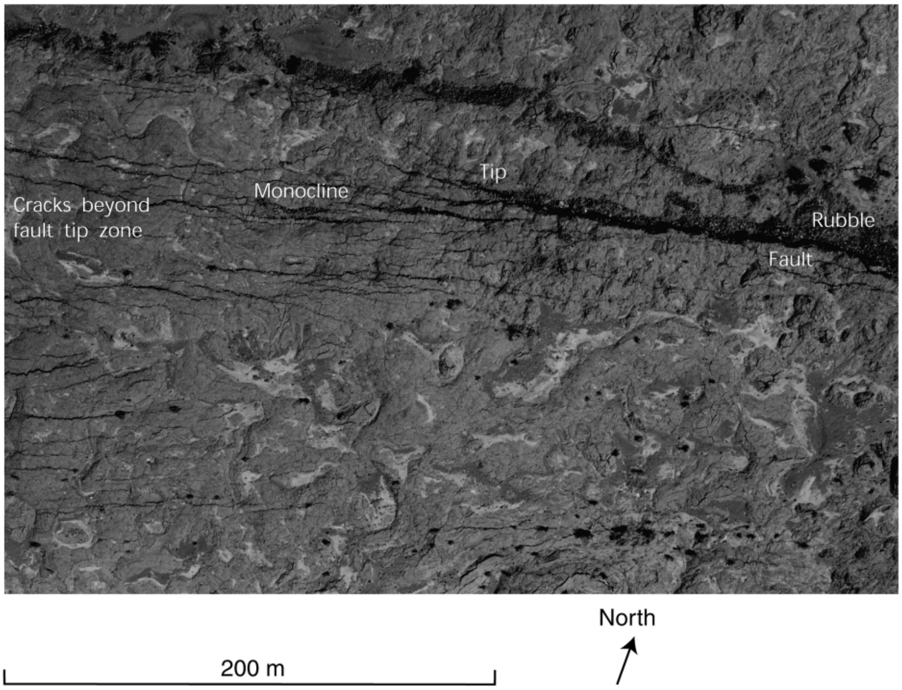


Fig. 6. Air photograph of a monocline developed at the tip of a normal fault segment. The normal fault has a throw of about 20 m, and is from the western tip of the fault in the NW of the mapped area of Fig. 3(b). Cracks intensity and monocline amplitude decreases away from the fault tip. The fault plane is marked by a zone of dilation and by rubble.

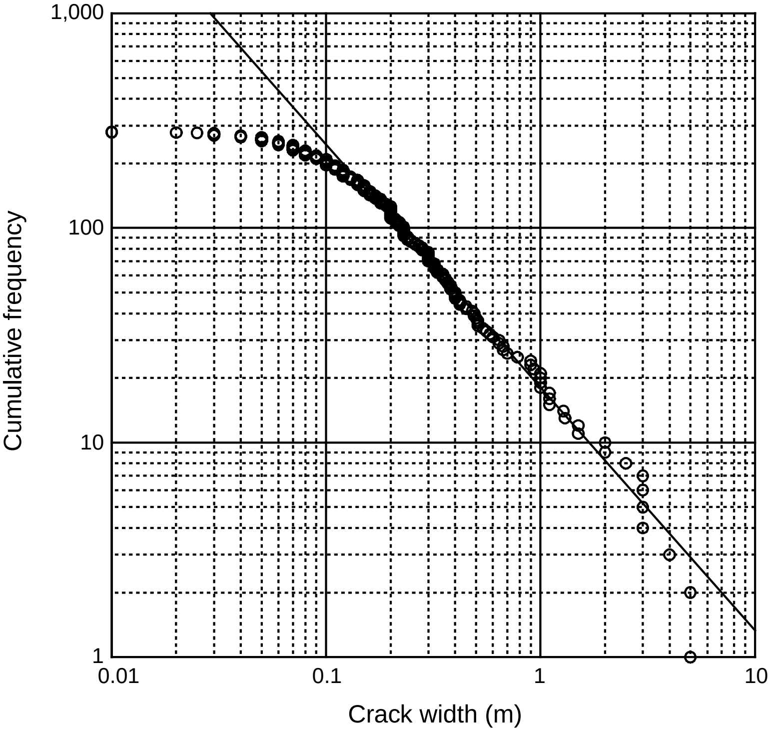


Fig. 7. Graph of crack widths in the mapped area of the Koae Faults (Fig. 3b). The power-law exponent, $D \approx 1.13$, $n = 280$. The cracks exhibit a power-law distribution from about 0.1 to 3 m. The lower cut-off may be because it is difficult to see cracks less than 0.1 m wide. The upper cut-off is because throw starts to occur on cracks more than about 3 m wide, which are then mapped as faults. The widths of faults are difficult to determine because of rubble.

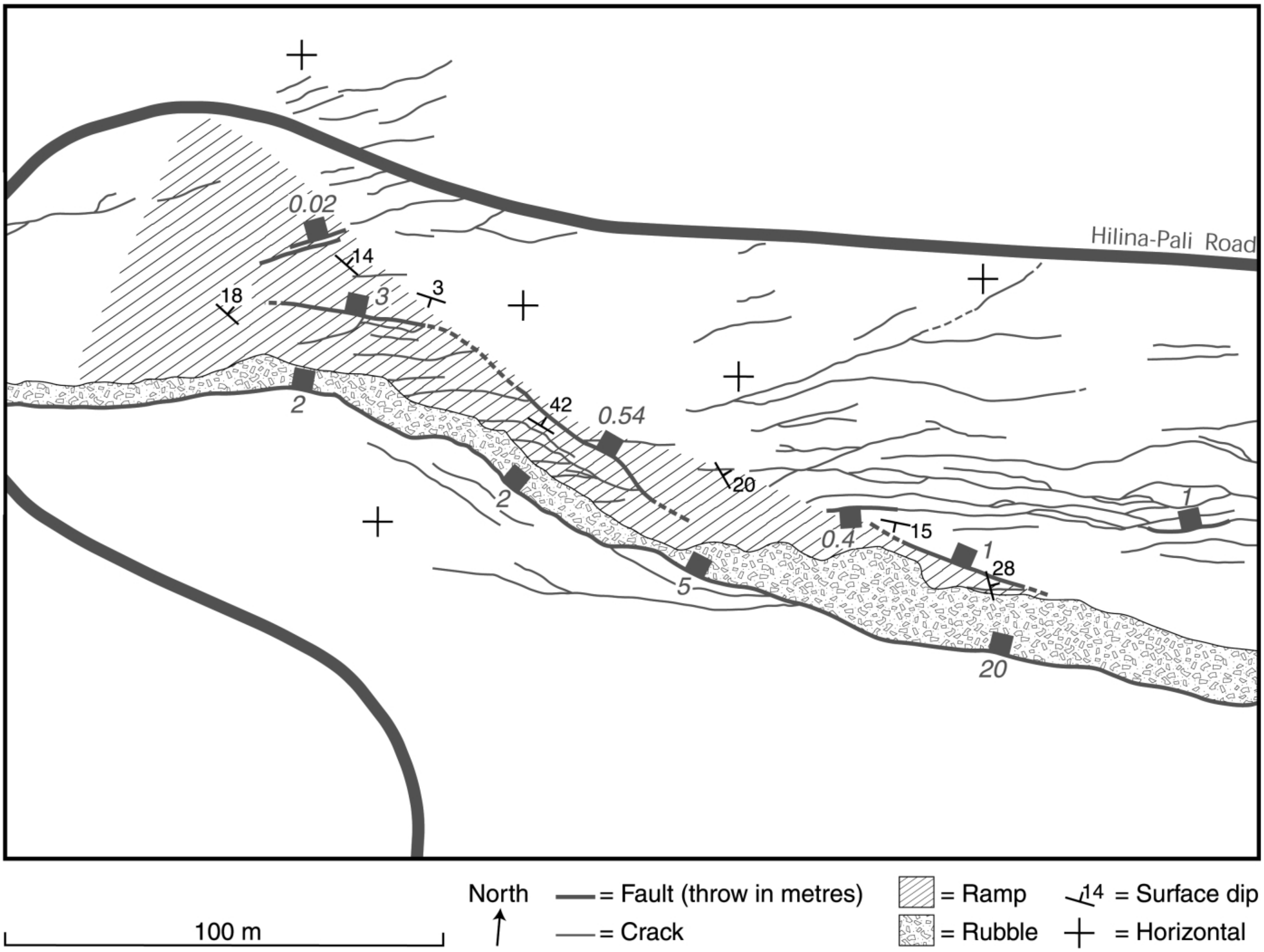


Fig. 8. Map of the breached relay ramp at bend of Hilina–Pali road. The air photograph of this area is shown in Fig. 3(a).

start to develop throw when they reach widths (apertures) of about 3 m. They are therefore mapped as faults. This is analogous to veining associated with normal faults in limestone and mudrock sequences described by Peacock and Sanderson (1992), where the veins with widths of more than 22 mm start to develop throw.

The frequency of the widths of fault-related cracks obey a power-law scaling relationship over more than an order of magnitude, from about 0.1 m to about 3 m (Fig. 7). Other studies have shown that frequencies of crack widths obey power-law scaling relationships (e.g. Barton and Zoback, 1992). The upper and lower limits of this relationship may be of significance. The cracks with widths of less than 0.1 m may be under-sampled because they are difficult to see, possibly being difficult to distinguish from fractures formed during lava flow and cooling. Alternatively, the power-law scaling relationship may break down, with relatively few narrow cracks occurring. It is possible that there are sampling biases that cause under-sampling of cracks with widths of more than 3 m (e.g. the mapped area was too small, and larger cracks were not sampled). It seems likely, however, that the data presented in Fig. 7 support the observation that cracks with widths of about 3 m start to develop throw, so they become faults.

Cracks are therefore unlikely to be more than about 3 m wide before throw develops. Vermilye and Scholz (1995) found length to width ratios for veins of $1:10^{-3}$ to $8:10^{-3}$. A 3-m-wide vein would therefore be 3–24 km long. These cracks are dissimilar to veins, but the widths and exposed trace lengths of cracks suggest they extend downward at least tens to hundreds of metres.

3. Relay ramps on Kilauea Volcano

3.1. Relay ramps within the Koae Fault System

The mapped area of the Koae Fault System shows (Fig. 3b) a good example of a relay ramp about 200 m across. The faults that bound the relay ramp understep by about 300 m and have up to at least 20 m throw, with downthrows to the north. A possible antithetic fault occurs within the relay

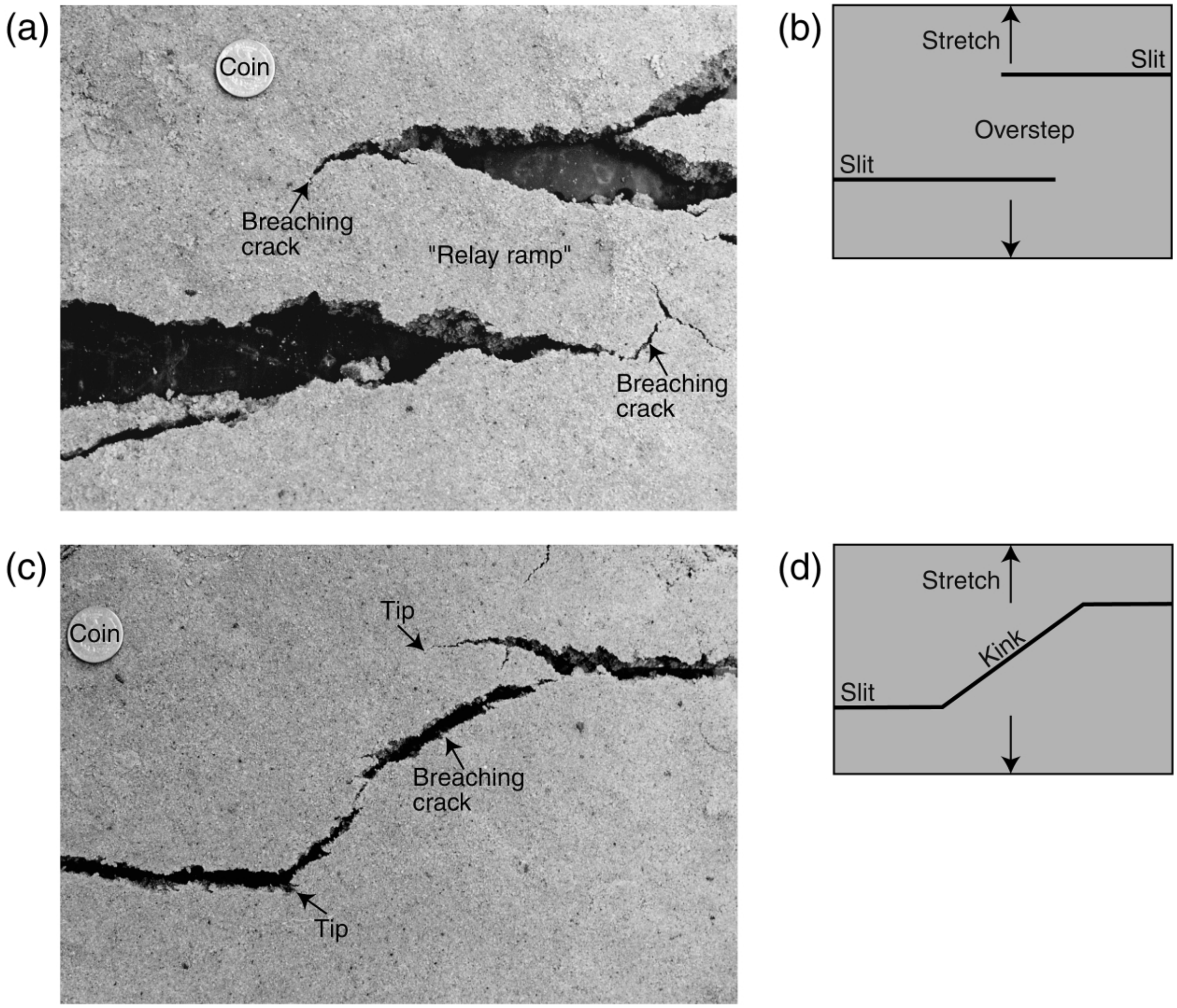


Fig. 9. Photographs and boundary conditions of two analogue models to illustrate the importance of fault connectivity at depth. Damp sand about 20 mm thick has been placed above a plastic sheet that is slowly stretched. The cracks are extension fractures, with no throw. A 24 mm diameter coin is used for scale. (a) The underlying sheet has two parallel, non-coplanar cuts to simulate faults that are unconnected at depth. The cracks in the sand show the start of tip-to-plane linkage to define a rhomb-shaped structure. (b) Boundary conditions for the model illustrated in (a). (c) The underlying plastic sheet has a single cut with a kink-shaped bend, to simulate faults that are connected at depth. The sand shows two understepping cracks, with a connecting crack extending from near the tip of one bounding crack to the plane the other crack to form a single curved crack. The fracture pattern is similar to relay ramps in the Koae and Hilina fault systems (e.g. Fig. 1b). Linkage has occurred at much lower extension than for the fractures that are not connected at depth (see part (a)). (d) Boundary conditions for the model illustrated in (c).

ramp, but this irregular structure may be a collapsed lava tube. The ground surface is irregular, so the dip of the relay ramp cannot be quantified. Any dip is probably, however, very gentle. Partial linkage between the two bounding faults is represented by en échelon cracks, which are mostly right-stepping. The cracks extend between the fault tips, but the monoclines at the fault tips extend for tens of metres beyond. This geometry suggests that the bounding faults connect downwards into a single fault, as was described for surface cracks along the Kaoiki Fault System by Jackson et al. (1992). A similar geometry occurs for surface ruptures at Kaparelli, Greece (Jackson et al., 1982). A difference is that the cracks in the relay ramp at Kaparelli are not en échelon and parallel to the faults, but splay between them. Huggins et al. (1995) suggest that ancient, exhumed relay ramps can be formed by faults that link at depth.

Other, smaller relay ramps occur within the mapped area. For example, a breached relay ramp occurs in the bend of Hilina–Pali Road (Fig. 8), where the ground surface dips steeply to the north or northeast, i.e. there is a component of dip towards the hanging wall. Segmentation and relay ramps are common elsewhere in the Koae Fault System (Fig. 2).

3.2. Relay ramps in the Hilina Faults System

Relay ramps in the Hilina Fault System (Figs. 1b and 2) are hundreds of metres across, and are larger than those exposed in the Koae Fault System. The faults have up to

500 m throw at the surface. The relay ramps tend to have greater rotation than the relay ramps in the Koae Fault System. This rotation includes an element of dip towards the hanging wall. This dip towards the hanging wall appears to be a common feature of relay ramps (Peacock and Sanderson, 1994; Huggins et al., 1995). The relay ramps are commonly partially or completely breached. Typically, a breaching fault or fault zone cuts across approximately the centre of the relay ramp from the plane of one bounding fault to the plane of the other. A good example of this is shown in Fig. 1(b), where a breaching fault zone extends from the plane of one bounding fault to the plane of the other bounding fault. This is different from the model of Peacock and Sanderson (1991, 1994) and of Crider and Pollard (1998), who show tip to plane linkage, with breaching faults cutting across one or both edges of a relay ramp. The reasons for this are discussed in Section 4.3.

The November 1975 earthquake involved about 25 km of surface rupturing along the Hilina Fault System, with up to 1.5 m throw on several segments that slipped synchronously (Lipman et al., 1985). This suggests the fault segments are connected at depth (Parfitt and Peacock, 2001). A model of the fault segments connecting down into a single fault at depth (Huggins et al., 1995) therefore seems appropriate.

4. The evolution of relay ramps at the Earth's surface

4.1. The evolution of relay ramps in the Koae and Hilina fault systems

Various relay ramp geometries occur in the Koae and Hilina fault systems (Figs. 1–3), and these geometries can be used to infer an evolutionary sequence for fault linkage (e.g. Peacock and Sanderson, 1991, 1994). Relay ramps with gentle ground surface dips, with few internal faults, and with understepping bounding faults that have gentle displacement gradients are inferred to be at an early stage of development. Relay ramps with steep ground dips, with breaching faults, and that have overstepping bounding faults with steep displacement gradients, are inferred to be at a later evolutionary stage. Three distinct stages can be identified. Stage 1 involves the bounding normal faults having low displacements and understep, so the relay ramp has a very gentle dip and little or no internal faulting (Fig. 3b). Cracks can link the two bounding faults, however, suggesting that the faults are connected at depth. Stage 2 involves the increase in dip and start of breaching of the relay ramp as displacement increases and the bounding faults overstep. An important difference with previous models for the evolution of relay ramps (e.g. Peacock and Sanderson, 1991, 1994) is that the breaching fault usually cuts across the centre of the relay ramp, between the planes of the two bounding faults (Fig. 1b). During stage 3, the relay ramp is breached to form a single irregular fault trace. An area where the ground surface dips steeply represents the old relay ramp (Fig. 8). This sequence may occur through time as displacement increases temporally. It is also possible that this sequence occurs down the dip of the faults, as displacement increases spatially (Fig. 5).

4.2. Simple analogue models of fault linkage

Simple modelling has been carried out using damp sand about 20 mm thick to test the effects of linkage at depth on fracture patterns at the surface (Fig. 9). The sand was placed above a plastic sheet that is slowly stretched manually. In the first model (Fig. 9a and b), the underlying sheet has two parallel, non-coplanar cuts to simulate faults that are unconnected at depth. The cracks in the sand overstep, with tip-to-plane linkage occurring to define a rhomb-shape block. This is analogous to the relay ramps in the Canyonlands National Park described by Trudgill and Cartwright (1994), which occur above a salt layer and so are presumably not directly connected at depth.

In the second model (Fig. 9c and d), the underlying plastic sheet has a single cut with a kink-shaped bend, to simulate faults that are connected at depth. The sand shows two understepping cracks, with a connecting crack extending from near the tip of one bounding crack to the plane of the other crack to form a single curved crack. The fracture pattern is similar to the mapped relay ramp in the Koae Fault System (Fig. 3) and to the relay ramp in the Hilina Fault System shown in Fig. 1(b). A breaching crack develops at much lower strains when the fractures are connected at depth (Fig. 9a). This may explain the set of en échelon cracks developed between the understepping bounding faults illustrated in Fig. 3(b).

4.3. Comparison with relay ramps in ancient, exhumed fault zones

Previous detailed work on the geometry and evolution of relay ramps has tended to look at extinct, exhumed faults. Trudgill and Cartwright (1994) describe the geometry of active relay ramps in Canyonlands National Park, Utah, but these involve a special case of faults that detach into a salt layer. The relay ramps described by Dawers and Anders (1995) and by Crider and Pollard (1998) may be active, but these studies do not present detailed field data. Peacock and Sanderson (1991, 1994) and Huggins et al. (1995) have illustrated evolutionary stages for extinct relay ramps. A wide variety of relay ramp geometries occur, and these can be classified into four groups based on the degree of interaction and linkage between the overstepping segments. Peacock and Sanderson (1994, their fig. 3) interpreted these four groups as evolutionary stages. At stage 1, the sub-parallel, non-coplanar fault segments do not interact. Stage 2 involves the rotation of bedding between two interacting faults to produce a relay ramp (e.g. Peacock and Sanderson, 1994, their fig. 5). At stage 3, connecting fractures start to break the relay ramp (e.g. Peacock and Sanderson, 1994, their figs. 7 and 10), so the relay ramp is breached (Childs et al., 1993). Stage 4 is when the relay ramp is broken to produce a single fault (e.g. Peacock and Sanderson, 1994, their fig. 10) that has an along-strike bend.

The evolution of relay ramps described by Peacock and Sanderson (1994) and by Huggins et al. (1995) is similar to the development of relay ramps on Kilauea Volcano (Section 4.1). The main difference is the style of the breaching faults. In the ancient exhumed relay ramps described by Peacock and Sanderson (1991, 1994), two breaching faults tend to cut from the tips of both bounding faults, along the hinges of the monocline that defines the relay ramp, to define a rhomb-shaped, fault-bounded block. Alternatively, only one breaching fault forms from the tip of one bounding fault (Peacock and Sanderson, 1994, their fig. 7). In the Koae and Hilina fault systems, however, one breaching fault cuts across the approximate centre of the relay ramp from the plane of one bounding fault to the plane of the other (Figs. 1b and 3). We suggest that this is caused by the central breaching fault being above an along-strike bend in the underlying fault zone, where a relay ramp has been fully breached to form a single fault.

4.4. Implications for seismic activity

An aim of this study of active relay ramps was to gain insights into the rupture behaviour of normal fault segments. It has been reported that rupture patterns and sequences can be controlled by bends along faults (e.g. King and Nábêlek, 1985) and by oversteps along normal faults (e.g. Crone and Haller, 1991; dePolo et al., 1991; Zhang et al., 1991; Gupta and Scholz, 2000), but there does not appear to have been an attempt to link relay ramp geometry to rupture behaviour.

We have examined accounts of rupture behaviour in the Basin and Range Province to test the effects of understep or overstep between the bounding faults in relay ramps. Zhang et al. (1991) describe the Dixie Valley–Pleasant Valley active normal fault system, Nevada, where there does not appear to be a correlation between amount of overstep and synchronous fault movement. The Dixie Valley segment was activated during the 1954 Dixie Valley earthquake, but the understepping Sand Spring segment was not active. The Stillwater segment, which oversteps both the Dixie Valley and Pleasant Valley segments, slipped during the 1954 Dixie Valley earthquake, but was not active during the 1915 Pleasant Valley earthquake. Similarly, Wallace (1984, plate A) shows two overstepping, apparently unconnected normal faults that were synchronously active during an earthquake in 1915. They were either connected at depth but not connected at the surface, or had coseismic behaviour. Thus, whether a fault understeps or oversteps at the surface is not a clear indicator of connectivity at depth or of the likelihood of simultaneous slip.

We suggest that breaching faults or cracks that cut across the centre of a relay ramp, like the type seen in the Koae and Hilina fault systems (Figs. 1–3), are indicative of fault linkage at depth. The analogue modelling (Fig. 9) supports this suggestion. In such cases, fault rupture and surface displacement could be expected on adjacent fault segments during a single earthquake event. Such synchronous slip occurred on the Hilina Fault System during the November 1975 earthquake (Lipman et al., 1985). Jackson et al. (1982) describe deformation at Kaparelli, Greece, during an earthquake in 1981, which is an excellent example of faults with synchronous slip with cracks cutting across the centre of the relay ramp. Such linkage may occur at an early stage in the development of a relay ramp (Fig. 9c), with linkage starting before the bounding faults overstep, high displacements build up, and before significant dip of the surface occurs.

The presence of cracks and small breaching faults across the centre of a relay ramp may be useful, therefore, because they indicate that synchronous slip may occur on the bounding faults. This would give valuable information about seismic hazards. The example described by Wallace (1984) indicates, however, that care is needed in interpretation because the lack of breaching faults or connecting cracks across the centre of a relay ramp does not necessarily mean that the bounding faults are unconnected at depth.

5. Conclusions

1. Four patterns of structures occur around the tips of fault segments in the Koae Fault System (Fig. 6). These are inferred to represent stages in the development of normal faults at the Earth's surface:
    1.1. A monoclinal flexure develops above a steeply dipping fault.
    1.2. Sub-vertical cracks develop in the axes of the monocline, especially in the outer-arc axis (nearest the footwall).
    1.3. The cracks connect with the normal fault, allowing throw to develop on one of the cracks.
    1.4. As displacement increases, hanging wall rollover occurs, largely because the fault is vertical at the surface but more gently dipping at depth.
2. Normal fault propagation on Kilauea Volcano involves the development of cracks beyond fault tips before or during faulting. The widths of cracks around the normal faults of the Koae Fault System obey a power-law between about 0.1 and 3 m. Cracks less than about 0.1 m wide may be under-sampled because they are difficult to see or because the power-law breaks down. When cracks reach a width of about 3 m, throw starts to occur and a fault develops (Fig. 7).
3. Various relay ramp geometries occur in the Koae and Hilina fault systems, and these are interpreted to represent three evolutionary stages (Fig. 5). First, two bounding faults understep to form a gently dipping relay ramp, but connection between the faults by en échelon cracks suggest that the faults link downwards into a single fault. Second, the faults overstep and the relay ramp dips as displacement increases. The relay

ramps starts to become breached by a fault between the two bounding faults. Third, the relay ramp is breached to form a single fault with an irregular trace. Simple analogue tests have been carried out to illustrate the importance of fault linkage at depth. Normal fault segments that are connected at depth tend to be characterised by plane-to-plane linkage across the middle of the relay ramp at an early stage of development, while faults that are not connected at depth are characterised by tip-to-plane linkage at higher strains (Fig. 9).

4. The presence of cracks or breaching faults across the centre of a relay ramp suggests that the bounding faults are connected at depth. This is supported by simple analogue modelling (Fig. 9). It also suggests that the bounding faults may both slip during an earthquake event. The amount of understep or overstep of the bounding faults in a relay ramp does not, however, give a clear indication of possible rupture behaviour. Care is needed in interpretation, because the lack of breaching faults across a relay ramp does not prove that the bounding faults are not connected at depth.

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References

Acocella, V., Salvini, F., Funiciello, R., Faccenna, C., 1999. The role of transfer structures on volcanic activity at Campi Flegrei (southern Italy). Journal of Volcanology and Geothermal Research 91, 123–139.

Acocella, V., Gudmundsson, A., Funiciello, R., 2000. Interaction and linkage of extension fractures and normal faults: examples from the rift zone of Iceland. Journal of Structural Geology 22, 1233–1246.

Anders, M.H., Schlische, R.W., 1994. Overlapping faults, intra-basin highs, and the growth of normal faults. Journal of Geology 102, 165–180.

Ando, M., 1979. The Hawaii earthquake of November 29, 1975: low dip angle faulting due to forceful injection of magma. Journal of Geophysical Research 84, 7616–7626.

Barton, C.A., Zoback, M.D., 1992. Self-similar distribution and properties of macroscopic fractures at depth in crystalline rock in the Cajon Pass scientific drill hole. Journal of Geophysical Research 97, 5181–5200.

Childs, C., Easton, S.J., Vendeville, B.C., Jackson, M.P.A., Lin, S.T., Walsh, J.J., Watterson, J., 1993. Kinematic analysis of faults in a physical model of growth faulting above a viscous salt analog. Tectonophysics 228, 313–329.

Crider, J.G., Pollard, D.D., 1998. Fault linkage: three-dimensional mechanical interaction between échelon normal faults. Journal of Geophysical Research 103, 24373–24391.

Crone, A.J., Haller, K.M., 1991. Segmentation and the coseismic behavior of Basin and Range normal faults: examples from east-central Idaho and southwest Montana, USA. Journal of Structural Geology 13, 151–164.

Dawers, N.H., Anders, M.H., 1995. Displacement-length scaling and fault linkage. Journal of Structural Geology 17, 607–614.

Denlinger, R.P., Okubo, P., 1995. Structure of the mobile south flank of Kilauea Volcano, Hawaii. Journal of Geophysical Research 100, 24499–24507.

dePolo, C.M., Clark, G.C., Slemmons, D.B., Ramelli, A.R., 1991. Historical surface faulting in the Basin and Range province, western North America: implications for fault segmentation. Journal of Structural Geology 13, 123–136.

Duffield, W.A., 1975. Structure and origin of the Koae Fault System, Kilauea Volcano, Hawaii. United States Geological Survey, Professional Paper 856.

Ferrill, D.A., Stamatakos, J.A., Sims, D., 1999. Normal fault corrugation: implications for growth and seismicity of active normal faults. Journal of Structural Geology 21, 1027–1038.

Gawthorpe, R.L., Hurst, J.M., 1993. Transfer zones in extensional basins: their structural style and influence on drainage development and stratigraphy. Journal of the Geological Society of London 150, 1137–1152.

Gillard, D., Wyss, M., Okubo, P., 1996. Type of faulting and orientation of stress and strain as a function of space and time in Kilauea's south flank, Hawaii. Journal of Geophysical Research 101, 16025–16042.

Goguel, J., 1952. Traité de Tectonique. Masson, Paris Translated by Thalmann, H.E., 1962. Tectonics. Freeman, San Francisco.

Got, J.L., Frechet, J., Klein, F.W., 1994. Deep fault plane geometry inferred from multiplet relative relocation beneath the south flank of Kilauea. Journal of Geophysical Research 99, 15375–15386.

Griffiths, P.S., 1980. Box-fault systems and ramps: atypical associations of structures from the eastern shoulder of the Kenya Rift. Geological Magazine 117, 579–586.

Gupta, A., Scholz, C.H., 2000. A model of normal fault interaction based on observations and theory. Journal of Structural Geology 22, 865–879.

Holcomb, R.T., 1987. Eruptive history and long term behavior of Kilauea volcano. United States Geological Survey, Professional Paper 1350, 261–351.

Huggins, P., Watterson, J., Walsh, J.J., Childs, C., 1995. Relay zone geometry and displacement transfer between normal faults recorded in coal-mine plans. Journal of Structural Geology 17, 1741–1755.

Jackson, J., Leeder, M., 1994. Drainage systems and the development of normal faults: an example from Pleasant Valley, Nevada. Journal of Structural Geology 16, 1041–1059.

Jackson, J., Gagnepain, J., Houseman, G., King, G.C.P., Papadimitriou, P., Soufleris, C., Vireux, J., 1982. Seismicity, normal faulting, and the geomorphological development of the Gulf of Corinth (Greece): the Corinth earthquakes of February and March 1981. Earth and Planetary Science Letters 57, 377–397.

Jackson, M.D., Endo, E.T., Delaney, P.T., Arnadottir, T., Rubin, A.M., 1992. Ground ruptures of the 1974 and 1983 Kaoiki earthquakes, Mauna-Loa volcano, Hawaii. Journal of Geophysical Research 97, 8775–8796.

King, G., Nábêlek, J., 1985. Role of fault bends in the initiation and termination of earthquake rupture. Science 228, 984–987.

Kinoshita, W.T., 1967. May 1963 earthquakes and deformation in the Koae Fault Zone, Kilauea Volcano Hawaii. United States Geological Survey, Professional Paper 575-C, C173–C176.

Klein, F.W., Koyanagi, R.Y., Nakata, J.S., Tanigawa, W.R., 1987. The seismicity of Kilauea's magma system. United States Geological Survey, Professional Paper 1350, 1019–1185.

Larsen, P.-H., 1988. Relay structures in a Lower Permian basement-involved extension system, East Greenland. Journal of Structural Geology 10, 3–8.

Leeder, M.R., Jackson, J.A., 1993. The interaction between normal faulting and drainage in active extensional basins, with examples from the western United States and central Greece. Basin Research 5, 79–102.

Lipman, P.W., Lockwood, J.P., Okamura, R.T., Swanson, D.A., Yamashita, K.M., 1985. Ground deformation associated with the 1975 magnitude 7.2 earthquake and resulting changes in activity of Kilauea volcano, Hawaii. United States Geological Survey, Professional Paper 1276.

Macdonald, G.A., 1957. Faults and monoclines on Kilauea Volcano, Hawaii. Bulletin of the Geological Society of America 68, 269–271.

Machette, M.N., Personius, S.F., Nelson, A.R., Schwartz, D.P., Lund, W.R., 1991. The Wasatch fault zone, Utah; segmentation and history of Holocene earthquakes. Journal of Structural Geology 13, 137–149.

Morgan, J.K., Moore, G.F., Hills, D.J., Leslie, S., 2000. Overthrusting and sediment accretion along Kilauea's mobile south flank, Hawaii: evidence for volcanic spreading from marine seismic reflection data. Geology 28, 667–670.

Morley, C.K., Nelson, R.A., Patton, T.L., Munn, S.G., 1990. Transfer zones in the East African rift system and their relevance to hydrocarbon exploration in rifts. Bulletin of the American Association of Petroleum Geologists 74, 1234–1253.

Owen, S., Segall, P., Freymueller, J., Miklius, A., Denlinger, R., Arnadottir, T., Sako, M., Burgmann, R., 1995. Rapid deformation of the south flank of Kilauea volcano, Hawaii. Science 267, 1328–1332.

Parfitt, E.A., Peacock, D.C.P., 2001. South flank faults and edifice deformation at Kilauea Volcano, Hawaii. Journal of Volcanology and Geothermal Research 106, 265–284.

Peacock, D.C.P., 2001. The temporal relationship between joints and faults. Journal of Structural Geology 23, 329–341.

Peacock, D.C.P., Sanderson, D.J., 1991. Displacements, segment linkage and relay ramps in normal fault zones. Journal of Structural Geology 13, 721–733.

Peacock, D.C.P., Sanderson, D.J., 1992. Effects of layering and anisotropy on fault geometry. Journal of the Geological Society of London 149, 793–802.

Peacock, D.C.P., Sanderson, D.J., 1994. Geometry and development of relay ramps in normal fault systems. Bulletin of the American Association of Petroleum Geologists 78, 147–165.

Peacock, D.C.P., Knipe, R.J., Sanderson, D.J., 2000. Glossary of normal faults. Journal of Structural Geology 22, 291–305.

Roberts, S., Jackson, J., 1991. Active normal faulting in central Greece: an overview. In: Roberts, A.M., Yielding, G., Freeman, B. (Eds.). The Geometry of Normal Faults. Geological Society Special Publication 56, London pp. 125–142.

Schlische, R.W., 1992. Structural and stratigraphic development of the Newark extensional basin, eastern North America: evidence for the growth of the basin and its bounding structures. Bulletin of the Geological Society of America 104, 1246–1263.

Stewart, I.S., Hancock, P.L., 1991. Scales of structural heterogeneity within neotectonic normal fault zones in the Aegean region. Journal of Structural Geology 13, 191–204.

Swanson, D.A., Duffield, W.A., Fiske, R.S., 1976. Displacement of the south flank of Kilauea Volcano: the result of forceful intrusion of magma into the rift zone. United States Geological Survey, Professional Paper 963.

Trudgill, B.D., Cartwright, J.A., 1994. Relay ramp form and normal fault linkages — Canyonlands National Park, Utah. Bulletin of the Geological Society of America 106, 1143–1157.

Vermilye, J.M., Scholz, C.H., 1995. Relation between vein length and aperture. Journal of Structural Geology 17, 423–434.

Wallace, R.E., 1984. Faulting related to the 1915 earthquakes in Pleasant Valley, Nevada. United States Geological Survey, Professional Paper 1274-A.

Walsh, J.J., Watterson, J., 1987. Distributions of cumulative displacement and seismic slip on a single normal fault. Journal of Structural Geology 9, 1039–1046.

Withjack, M.O., Callaway, J.S., 2000. Active normal faulting beneath a salt layer: an experimental study of deformation in the cover sequence. Bulletin of the American Association of Petroleum Geologists 84, 627–651.

Wolfe, E.W., Morris, J., 1996. Geologic map of the island of Hawaii. United States Geological Survey, Map I-2524-A.

Wu, D., Bruhn, R.L., 1994. Geometry and kinematics of active normal faults, south Oquirrh Mountains, Utah: implications for fault growth. Journal of Structural Geology 16, 1061–1075.

Wyss, M., Klein, F.W., Johnston, A.C., 1981. Precursors to the Kalapana $M = 7.2$ earthquake. Journal of Geophysical Research 86, 3881–3900.

Zhang, P., Slemmons, D.B., Mao, F., 1991. Geometric pattern, rupture termination and fault segmentation of the Dixie Valley–Pleasant Valley active normal fault system, Nevada, USA. Journal of Structural Geology 13, 165–176.