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Glossary of normal faults

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Abstract

Increased interest in normal faults and extended terranes has led to the development of an increasingly complex terminology. The most important terms are defined in this paper, with original references being given wherever possible, along with examples of current usage.

1. Introduction

The large amount of work on normal faults over the last few decades has led to the introduction of many new terms and some confusing terminology. For example, the term *relay ramp* (Larsen, 1988) has also been applied to structures in strike-slip fault zones (e.g. Herzer and Mascle, 1996), and other terms have been applied to relay ramps in normal fault systems (e.g. *accommodation zone*, *fault bridge*, *transfer zone*).

The aim of this glossary is to give definitions of the most important terms currently used in connection with normal faults (Fig. 1). The glossary is intended for non-specialists who have not read the large number of recent papers about normal faults. Other general terms for faults are available in standard textbooks (e.g. Ramsay and Huber, 1987; Price and Cosgrove, 1990; Twiss and Moores, 1992), as are general terms used in structural geology (such as *strain* and *stress*). Similar glossaries for thrusts are given by Butler (1982) and by McClay (1992), and for strike-slip faults by Biddle and Christie-Blick (1985). We have attempted to find the first usage, or the earliest reasonable usage, of terms. A problem encountered when attempting to find first usage is that many terms were first used in the mining or hydrocarbon industries, gradually creeping into the geologic literature (e.g. *inversion* and *accommodation zone*). Where usage has changed through time (e.g. *horse*), we provide examples of current popular usage.

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Glossary

Accommodation zone: The area between two sub-parallel, non-collinear, overlapping faults (e.g. Reynolds and Rosendahl, 1984). Rosendahl et al. (1986, fig. 8) define an *accommodation zone* as transferring displacement or strain from one *half-graben* to another with opposite sense via oblique shear along an inter-basinal ridge. See *transfer zone*. For a discussion of the Faulds and Varga (1998) redefinition of *accommodation zone*, see *transfer zone*.

Antithetic fault: Defined by Cloos (1928) and Hills (1940, fig. 41) as a minor fault that dips in the opposite direction to the dip direction of the beds they displace. *Antithetic fault* is now commonly used for a fault that dips in the opposite direction to a related dominant fault or fault set, while *antithetic* is the relationship whereby two related faults have the opposite shear sense (e.g. Gibbs, 1984) (Fig. 1). For example, a normal fault with a downthrow to

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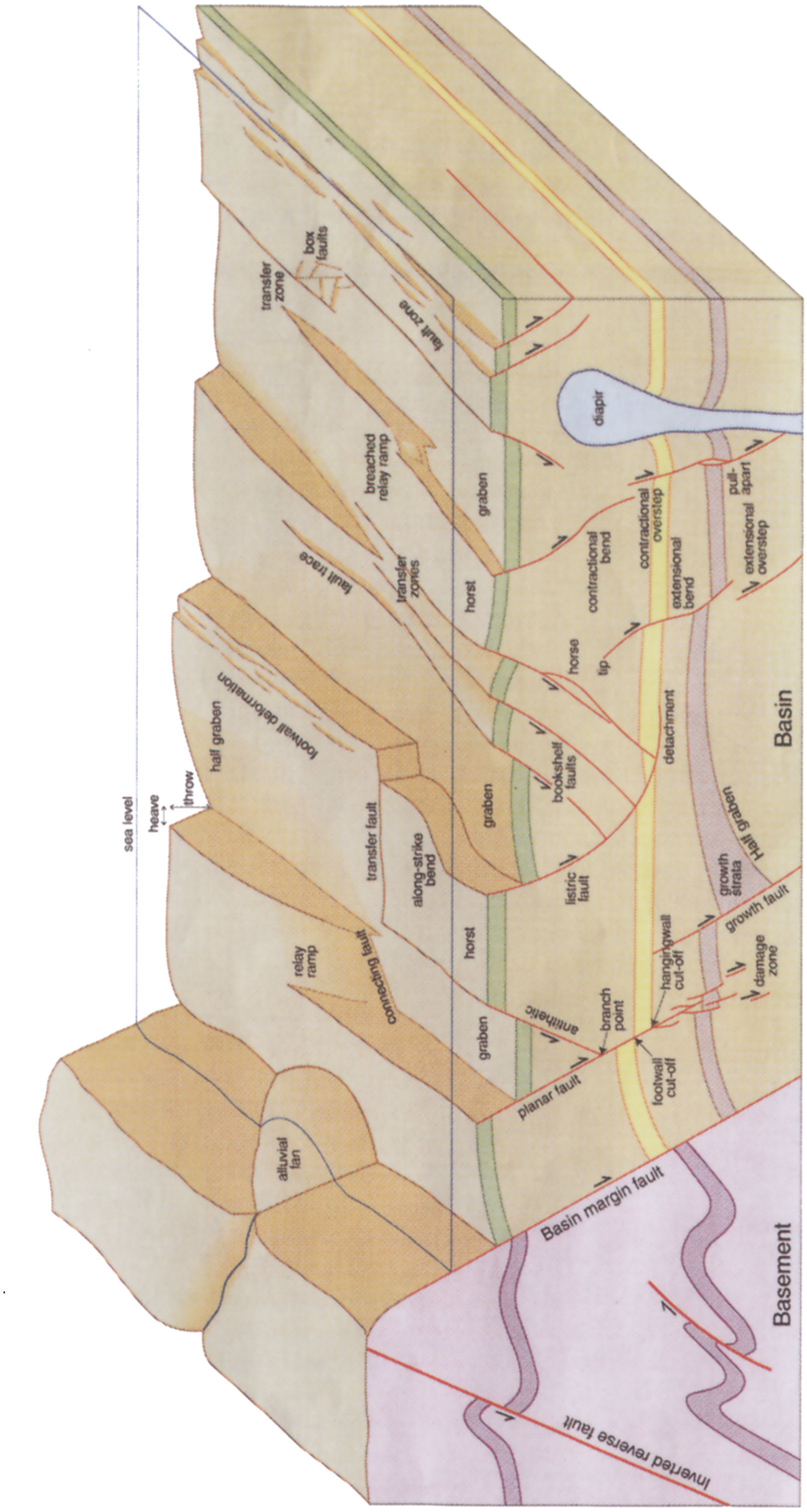

Fig. 1. Schematic block diagram showing the main geometric features of normal faults. The terms used are defined in the text.

the north is *antithetic* to a larger normal fault with a downthrow to the south. See *synthetic fault*.

Array, fault: A set of overstepping and en échelon fracture *segments* or fault zones (e.g. Segall and Pollard, 1980).

β-value: The *stretching factor*, defined as the increase in length of a cross-section due to extension (McKenzie, 1978; Barton and Wood, 1984), i.e. l_1/l_0, where l_0 = the original length and l_1 = deformed length.

Basement fault: A fault that cuts the basement and that originated before deposition of the cover sediments and that may be reactivated (e.g. Stewart et al., 1997). *Basement* is used here to refer to those rocks that formed before the basin in which the cover rocks are deposited.

Basin: Greenough (1819, p. 66) states that "when masses or strata decline upon every side towards a certain point, they are said to be basin-shaped". *Basin* is now usually defined as an area of subsidence in which sediments are deposited, with subsidence commonly being controlled by normal faults (e.g. Gibbs, 1984) (Fig. 1). Pull-apart basins can be controlled by strike-slip faults (e.g. Rodgers, 1980), whereas foreland basins are controlled by thrust faults (e.g. DeCelles and Giles, 1996).

Basin-margin fault: A fault that marks the edge of, and typically controls, a basin (e.g. Roberts and Yielding, 1991) (Fig. 1). Also see *border-fault system* and *boundary fault*.

Bend, along-strike: A bend in a fault in map view (Fig. 1). An along-strike bend on a normal fault is neither dominantly *extensional* or *contractional*, and commonly results from the linkage of two segments across a *relay ramp* (Peacock and Sanderson, 1991, 1994).

Bend, contractional: A spatial variation in the orientation of a fault-plane that causes local contraction in the wall-rocks as they are displaced around the bend (e.g. Peacock and Zhang, 1994). Such bends occur down the dip of normal faults where there is a local decrease in fault dip (Fig. 1). Synonymous with *closing bend*, *convergent bend* (Biddle and Christie-Blick, 1985) and with *restraining bend* (Crowell, 1974, fig. 3).

Bend, extensional: A spatial variation in the orientation of a fault-plane that causes local extension in the wall-rocks as they are displaced around the bend (e.g. Peacock and Zhang, 1994). Such bends occur down the dip of normal faults where there is a local increase in fault dip (Fig. 1). Synonymous with *divergent-bend*, *opening-bend* (Biddle and Christie-Blick, 1985) and with *releasing-bend* (Crowell, 1974, fig. 3).

Bend, fault: A spatial variation in the orientation of a fault-plane. Sibson (1989, fig. 6) uses *isolated fault bend* for a geometry in which a tip portion has a different orientation from the main part of the fault.

Block, fault: A fault-bound volume of rock (e.g. Diller, 1886; Stoces and White, 1935, fig. 327). Synonymous with *horse*.

Bookshelf faults: A system of sub-parallel faults that involve the progressive rotation of beds and faults as displacement occurs (e.g. Mandl, 1987) (Fig. 1). The *bookshelf mechanism* was defined by Mandl (1984) as simple shearing or extension accommodated by rotation of parallel faults in an array. Bookshelf normal faults tend to cause steepening of beds, and a decrease in the dip of the faults. Bookshelf faults can pass into a *detachment* or into a zone of ductile deformation (Mandl, 1987, fig. 4). See *domino faults*.

Border-fault system: Synonymous with *basin-margin fault* (Schlische, 1992).

Boundary fault: Synonymous with *basin-margin fault* (Morley, 1995).

Box faults: A *network* of faults developed between two *overstepping* normal faults (*relay ramp*) (Fig. 1), described in the East African Rift by Griffiths (1980).

Branch: One or more faults that extend off a larger fault (e.g. Nevin, 1931; Butler, 1982) (Fig. 1).

Branch line: A line along which two fault planes intersect (Butler, 1982).

Bridge, fault: Synonymous with *relay ramp* (Ramsay and Huber, 1987, fig. 23.50).

Cataclasis: Process involving brittle fragmentation of minerals, with rotation of grain fragments, grain-size reduction, grain boundary sliding and volume increase (definition of Sibson, 1977). Cataclasis typically occurs along fault planes or in zones of brittle deformation. Earlier usage of *cataclasis* is given by Sibson (1977).

Coherence, geometric: The existence of regular and systematic displacement patterns in a family of faults (Walsh and Watterson, 1991, fig. 4).

Coherence, kinematic: The existence of synchronous slip rates and slip distributions that are arranged such that *geometric coherence* is maintained (Walsh and Watterson, 1991).

Conjugate: For faults, *conjugate* refers to the relationship between two intersecting sets of faults that each formed under the same stress field (Daubrée, 1878, cited by Dennis, 1967). Two conjugate faults have the opposite shear sense and the same angle (generally $\approx 30°$) to the maximum principal stress direction (Anderson, 1951). Interacting conjugate faults may move alternately (Freund, 1974; Horsfield, 1980), or may move synchronously to form an area of high strain near the intersection (Peacock, 1991; Odonne and Massonnat, 1992). See *antithetic* and *synthetic*.

Connecting fault: A fault that connects two *overstepping* faults across a *transfer zone* or *relay ramp* (Peacock and Sanderson, 1994) (Fig. 1). Synonymous with *connecting splay* (Ramsay and Huber, 1987, fig. 23.50b).

Crestal collapse faults: Faults that develop in the crest of an anticline and that accommodate extension in the hinge region (e.g. McClay and Scott, 1991). Crestal faults in folds are described by DeSitter (1956, chapter 14). Crestal collapse faults can be normal or reverse, both of which can develop synchronously (Nieuwland and Walters, 1993, fig. 5).

Cut-off line: The line marking the boundary between a fault surface and a planar marker (bed, dyke, etc.) that is displaced by the fault (e.g. Suppe, 1985, fig. 2-28). See *footwall cut-off* and *hanging wall cut-off*. Synonymous with *footwall trace* and *hanging wall trace* of Gill (1935).

Damage zone: Location at which a major change in fabric (e.g. caused by pressure solution) is readily visible (Chester and Logan, 1986; Wu and Groshong, 1991), or the area of fracturing around and related to a fault (McGrath and Davison, 1995) (Fig. 1). Damage zones are typically caused by *fault propagation*, *linkage* or displacement along the fault (e.g. Cowie and Scholz, 1992b). Synonymous with *deformation front* and *texture zone* (Wu and Groshong, 1991).

Décollement: A bedding- or layer-parallel fault or shear zone, above which the rocks may be deformed (e.g. Lees, 1952; Ramsay and Huber, 1987). The process of *décollement* is described by DeSitter (1956) as the detachment of the upper cover from its substratum. Earlier usage of *abscherung* is described by Lees (1952). See *detachment*.

Deformation band: A planar zone of distributed deformation in which the strain is approximately simple shear, typically involving micro-fracturing and *cataclasis* (e.g. Aydin, 1978). See *granulation seam*.

Density, fault: A measure of the number of faults in a rock mass (e.g. Gillespie et al., 1993). Fault density may be measured in one, two or three dimensions, respectively as: (i) the number of faults per unit distance (usually measured perpendicular to the fault set); (ii) the total length of fault trace per unit area; or (iii) the total area of fault plane per unit volume. The unit of fault density is m^{-1} and is inversely proportional to *fault spacing*.

Detachment: Fault along a basal surface, along which overlying strata are detached (Pierce, 1963). *Detachment* is now commonly used for a regionally extensive, gently dipping normal fault (Fig. 1); they are commonly associated with extension in *metamorphic core complexes* and can displace crystalline rocks. Although the term is often used synonymously with *décollement*, Ramsay and Huber (1987) suggest that detachments are low-angle faults that are nearly, but not exactly, parallel to any one horizon.

Diapir: Originally used by Mrazec (1915, cited by Price and Cosgrove, 1990) for salt bodies in the cores of domes and anticlines. *Diapir* is now commonly used for any body of rock that behaved as a fluid over the time-scale during which it was emplaced upwards through brittle rocks by buoyancy-driven flow. Diapirs include certain igneous intrusions and salt domes. They are commonly accommodated by normal faults (e.g. Davison et al., 1996, fig. 7) (Fig. 1). See *halokinesis*.

Dilation: An increase (*positive* dilation) or a decrease (*negative* dilation) in volume (e.g. Price and Cosgrove, 1990).

Dilational jog: Synonymous with *extensional overstep* or *pull-apart* (Sibson, 1989, fig. 6).

Dip separation: The separation of a marker plane measured parallel to the dip of a fault (e.g. Gill, 1935; Hills, 1940). For a purely *dip-slip* fault (i.e. normal or thrust fault), the *dip separation* is identical to the *displacement* of the fault.

Dip-slip: The component of *displacement* parallel to the dip of the fault plane (cf. strike-slip) (Reid et al., 1913). Normal and thrust faults are both *dip-slip faults*, being dominated by dip-slip displacement (e.g. Reid et al., 1913).

Displacement: The relative movement between two originally adjacent points on the surface of a fault, i.e. the magnitude of the *displacement vector* (e.g. Leith, 1923). The displacement can be curved, so need not be a direct line between two originally adjacent points.

Displacement–distance (d–x) analysis: A method used to illustrate how displacement varies along a geological structure. The method has been used to describe the displacement gradient of faults, dykes, etc., and thereby infer their development (Muraoka and Kamata, 1983; Williams and Chapman, 1983; Chapman and Williams, 1984; Pollard and Segall, 1987; Walsh and Watterson, 1987). Procedure: (i) start at a fault tip (distance, $x_0 = 0$, displacement, $d_0 = 0$); (ii) at distance x_1 along the fault trace, measure displacement d_1; (iii) at distance x_2 along the fault trace, measure displacement d_2; (iv) repeat the process as many times as possible along the trace of the fault; (v) plot a graph of displacement (y-axis) against distance (x-axis).

Displacement–distance analysis, cumulative: A method of analysing how displacement varies in a family of faults (Chapman and Williams, 1984). Procedure for analysing normal or thrust faults in cross-section: (i) select a point on a marker bed along a cross-section; (ii) follow the bed and measure displacement (d_1) and distance (x_1) for the first fault; (iii) measure displacement (d_2) and distance (x_2) for the second fault; add d_1 to d_2; (iv) continue the process for all of the faults in the section; (v) plot a graph of cumulative displacement (y-axis) against distance (x-axis).

Displacement–length ratio: Maximum displacement on a fault surface or a fault trace, divided by the fault *length* or the trace length (see Barnett et al., 1987; Walsh and Watterson, 1988; Cowie and Scholz, 1992a; Gillespie et al., 1992; Dawers et al., 1993). The *slip* to length ratio for slip during large earthquakes is discussed by Scholz et al. (1986). Some authors use *length–displacement ratio*.

Displacement vector: The magnitude and orientation of the line connecting two originally adjacent points in the *hanging wall* and *footwall* of a fault. See *displacement*.

Domino faults: System of planar rotating normal faults, in which the dip of a particular stratigraphic datum is approximately constant (e.g. Twiss and Moores, 1992). An example of domino faults is shown by Ransome et al. (1910, fig. 15), but *domino fault* was not used. Domino faults can pass down into a *detachment*. Synonymous with *bookshelf faults* (e.g. Ramsay and Huber, 1987, fig. 23.19) and with *rotational planar normal faults* of Wernicke and Burchfiel (1982). Gamond (1983), however, uses *domino* for a rhomb-shaped, mineralised area at an *extensional overstep* (synonymous with *pull-apart*).

D-value: The power-law exponent (D) for the displacements of a *fault population*, such that $N = c \times U^{-D}$, where N = number of faults with a displacement greater than U, and c is a constant (e.g. Walsh and Watterson, 1992; Gillespie et al., 1993). Synonymous with *C-value* of Marrett and Allmendinger (1991).

Effective tension: The condition in which fluid pressure exceeds the least compressive stress, enabling *extension fractures* to form (see Hubbert and Rubey, 1959).

Extension: The increase in the length of a line, such that extension, $e = (l_1 - l_0)/l_0$, where l_0 = original length of the line, and l_1 = new length of the line. Extension can be positive, so the line increases in length, or negative, so that contraction occurs. *Regional extension* refers to deformation dominated by extension in one horizontal direction.

Extension(al) fault: A fault causing extension in the horizontal plane, i.e. normal and normal/oblique-slip faults (e.g. Goguel, 1952). Often used synonymously with *normal fault*.

Extension(al) fracture: A fracture produced by opening approximately perpendicular to the walls, and that usually propagated as a mode I crack (Pollard and Segall, 1987). Extension fractures are usually formed in *effective tension*, i.e. high pore-fluid pressure (e.g. Gross and Engelder, 1995). Filled extension fractures include dykes and veins.

Fault-bend fold: A fold developed in the *wall-rocks* to accommodate displacement around a *fault bend*. A detailed description is given by Suppe (1985). See *fault-related fold*.

Fault juxtaposition diagram: A diagram used to predict the juxtapositions of *hanging wall* and *footwall* lithologies for a given fault geometry and displacement (Knipe, 1997). It can be used to estimate the *sealing* potential of a fault.

Fault-line scarp: A steep slope or cliff formed by differential erosion along a fault, the height of which may not reflect relative movement on the fault (e.g. Rajendran et al., 1996). See *fault scarp*.

Fault population: The faults of all scales that exist in an area or region, formed during one or more deformation events. *Fault population analysis* involves the study of the scaling relationships and strain of the faults (e.g. Cowie et al., 1996). See *fractal* and *power-law*.

Fault-related fold: A fold developed in one or both of the *walls* of a fault or at the fault tip, caused by fault *propagation*, drag or by the non-planar geometry of the fault (e.g. Rich, 1934; Dahlstrom, 1970; Anastasio et al., 1997). A *break thrust* (a fold cut by a thrust) is shown by Willis (1839), and various fault-related folds are shown by Stoces and White (1935, figs. 286–291). Recent descriptions of folds that are related to the propagation of normal faults in map view are given by Schlische (1995) and by Janecke et al. (1998), while Hardy and McClay (1999) describe folds related to normal fault propagation in cross-section.

Fault rock: Rock along a fault plane with texture and/or chemical composition controlled by deformation and alteration along the fault. Accounts and classifications of fault rocks include those by Hobbs et al. (1976) and Sibson (1977).

Fault-rock width: See *thickness, fault*.

Fault scarp: Defined by Leith (1923) as a landform caused at the Earth's surface by fault movement or by later erosion along the fault that leaves one side of the fault plane standing higher than the other side. Common usage is now for a tectonic landform coincident, or roughly coincident, with a fault plane that has dislocated the ground surface, i.e. it has not been strongly modified by weathering and erosion (Stewart and Hancock, 1990). See *fault-line scarp*.

Fault strain: Used by Jamison (1989) to describe the deformation caused by a number of faults, because *strain* should only be applied to continuous deformation.

Flexural uplift or subsidence: Buoyancy-induced vertical (isostatic) deformation that decreases in magnitude away from a fault (e.g. Egan, 1992). Flexural uplift and subsidence are typically modelled as an elastic response to fault slip (e.g. Roberts and Yielding, 1991). Flexural explanations are commonly accepted for certain cases of *footwall uplift* and *hanging wall subsidence.*

Flower structure: A system of faults that *splay* upward within a strike-slip fault zone (Harding and Lowell, 1979). *Negative* flower structures involve steepening upwards extensional splay faults, whereas *positive* flower structures involve shallowing upwards contractional splay faults (Harding, 1983, 1985).

Footwall: An old mining term for the rock mass that is below a lode or fault; early usage of *footwall* is given by Dennis (1967). *Footwall* has been extended to include the volume of rock below a dipping fault, i.e. the upthrown side of a normal fault.

Footwall cut-off: The line in the footwall marking the boundary between a fault surface and a planar marker (bed, dyke, etc.) that is displaced by the fault (e.g. Gibson et al., 1989) (Fig. 1). Synonymous with *footwall trace* (Gill, 1935). See *cut-off* and *hanging wall cut-off.*

Footwall uplift: Uplift that occurs below a fault, e.g. in the footwall of a normal fault (e.g. Jackson and McKenzie, 1983). Synonymous with *rollunder* (Barnett et al., 1987). See *flexural uplift* and *hanging wall subsidence.*

Fractal: The geometry whereby objects are scale independent, being *scale invariant* at all scales between upper and lower limits; any portion of the system is geometrically similar to the whole system (Mandlebrot, 1982; Turcotte, 1989; Gillespie et al., 1993). For natural objects, *fractal* is generally used if the statistical properties are *scale invariant* and exhibit a *power-law distribution.* Normal faults have been shown to be fractal (e.g. Scholz and Cowie, 1990; Marrett and Allmendinger, 1992).

Fracture: Geological fractures include such approximately planar discontinuities as dykes, faults, joints and veins. Appears to be synonymous with *discontinuity* (Priest and Hudson, 1976, 1981).

Fracture nucleation: The initiation of a fracture that then *propagates* (e.g. Segall and Pollard, 1983; Reches and Lockner, 1994).

Gouge: Defined by Reid et al. (1913) as pulverised rock, generally clay-like when moist, that occurs between the walls of a fault. Defined by Sibson (1977, table 1) as an incohesive fault rock with a random fabric in which fragments comprise $<30\%$ of the rock mass.

Graben: Long and relatively narrow area of subsidence mostly bounded by sub-parallel normal fault zones that dip towards the area of subsidence (Reid et al., 1913; Dennis, 1967) (Fig. 1). Grabens are commonly bounded by *horsts. Graben* originated as a German mining term (Dennis, 1967). See *rift.*

Granulation seam: A planar zone of deformation in which poorly consolidated grains move past each other (e.g. Pittman, 1981). Synonymous with *deformation band* (Knott, 1994).

Growth fault: A normal growth fault is characterised by: (a) an increase in displacement down the dip of the fault; and by (b) thicker sediments in the *hanging wall* near the fault than in the *footwall* or in the *hanging wall* away from the fault (Ocamb, 1961) (Fig. 1). This implies that, during sedimentation, the fault was active and cut the Earth's surface. Synonymous terms are given by Dennis (1967).

Growth-fault basin: Basin that thickens towards, and is related to, a *growth fault* (e.g. Harms and Price, 1992).

Half-graben: Asymmetric area of subsidence controlled by *hanging wall subsidence* above a single controlling (*basin-bounding*) fault (e.g. Barr, 1987) (Fig. 1). A half-graben typically contains a *hanging wall* sedimentary wedge that thickens towards the fault, with older beds having steeper dips than younger beds. *Rollover* in a half-graben can be controlled by a *listric* fault, while recent interpretations have involved approximately planar faults (e.g. Roberts and Yielding, 1991, figs. 1 and 4). See *flexural subsidence.*

Halokinesis: Proposed by Trusheim (1957, cited by Trusheim, 1960) for the formation of salt structures, and their structural and stratigraphic implications, resulting from autonomous movement of salt driven by gravity (e.g. Stewart and Coward, 1995). Halokinesis is commonly accommodated by normal faults (e.g. Koestler and Ehrmann, 1991). See *diapir.*

Hanging wall: An old mining term for the rock mass that is above a lode or fault; early usage of *hanging wall* is given by Dennis (1967). Hanging wall has been extended to include the volume of rock above a dipping fault, i.e. the downthrown side of a normal fault.

Hanging wall cut-off: The line in the *hanging wall* that marks the boundary between a fault surface and a planar marker (bed, dyke, etc.) that is displaced by the fault (e.g. Gibson et al., 1989) (Fig. 1). Synonymous with *hanging wall trace* (Gill, 1935). See *cut-off* and *footwall cut-off.*

Hanging wall subsidence: The downward movement of the *hanging wall* of a normal fault (e.g. Jackson and McKenzie, 1983). *Hanging wall* subsidence is illustrated by DeSitter (1956, fig. 73). See *footwall uplift.*

Hard-linkage: The geometry or process whereby two faults are connected by one or more (usually smaller) faults that are visible at the scale of observation (Walsh and Watterson, 1991). See *connecting faults* and *soft-linkage*.

Heave: Defined by Geikie (1882) as a horizontal displacement of strata at a fault. Defined more fully by Hills (1940) and by Billings (1942) as the horizontal component of the *dip-separation* of a normal or reverse fault measured in vertical cross-section perpendicular to the fault strike (Fig. 1). *Heave* is defined in terms of the *separation*, hence it applies to the faulted geometry of a plane and not to the displacement of the fault. Only for a pure *dip-slip* fault (no oblique-slip component) is the heave equivalent to the horizontal component of the *displacement*. See *throw*. Early usage is given by Dennis (1967).

Horse: Usage of the old mining term *horse* has changed. For example, Mills (1790) appears to use *horse* to mean *dyke*. *Horse* is now defined as a fault-bound block of rock (e.g. Butler, 1982). In a normal fault system, horses can represent a *breached relay ramp* (Peacock and Sanderson, 1994) (Fig. 1). See *block, fault*.

Horst: Elongate area of uplift mostly bounded by sub-parallel normal fault zones that dip away from the area of uplift (e.g. Reid et al., 1913; Dennis, 1967) (Fig. 1). Horsts are commonly bounded by *grabens* or *half-grabens*.

Interaction, fault: Mechanical interaction between faults involves the behaviour and development of one fault being influenced by another fault or faults (e.g. Segall and Pollard, 1980; Aydin and Schultz, 1990; Bürgmann et al., 1994). *Overstepping* normal faults interact across *transfer zones* (Morley et al., 1990). *Rift* interaction is described by Nelson et al. (1992).

Inversion: Originally used for the overturning of strata, so the sequence is reverse (e.g. Murchison, 1859). *Inversion* is now commonly used for the *reactivation* of a dip-slip fault such that there is a reversal of the sense of throw (e.g. Stoneley, 1982; Buchanan and Buchanan, 1995). *Reverse-reactivation* of a normal fault or the contraction of a region that previously underwent extension is termed *positive inversion*. Alternatively, *negative inversion* is the normal-reactivation of a reverse fault or the extension of a region that previously underwent contraction (e.g. Williams et al., 1989). For a discussion of the usage of *inversion* and *reactivation*, see Needham (1989).

Isolated fault: A fault that was not affected by *interaction* with other faults during its *propagation* (e.g. Muraoka and Kamata, 1983; Walsh and Watterson, 1987). An isolated fault is usually characterised by a displacement maximum near the centre of the fault trace, with displacement decreasing approximately linearly towards the tips (Barnett et al., 1987; Walsh and Watterson, 1987). Harding and Lowell (1979) describe *solitary* structures, that are isolated, singular features. Nicol et al. (1996) describe *unrestricted* faults, that are blind (do not intersect the free surface) and that have not interacted with other faults or with substantial bodies of incompetent rock.

Jog: Used by Sibson (1989, fig. 6) for an *overstep* or *bend* that connects two sub-parallel but non-collinear portions of a fault zone. Sibson (1989) divides jogs into *dilational* and *anti-dilational*, that are *extensional* and *contractional*, respectively.

Length, fault: The distance between the tips of a fault, usually measured along a fault trace and in the horizontal plane (e.g. Scholz and Cowie, 1990; Peacock, 1991). Synonymous with *trace length*. Note, however, that *length* is used by Barnett et al. (1987) and by Walsh and Watterson (1988, fig. 1) for the maximum distance parallel to the slip direction of a fault.

Linkage: The process by which, or condition in which, two originally separate faults become connected (Pollard and Aydin, 1984).

Listric: Introduced by Suess (1909) for an originally curved fault, supposedly because it is ancient Greek for *shovel*. When applied to normal faults, *listric* usually indicates a decrease in dip downwards (e.g. Davison, 1986; Williams and Vann, 1987). Listric normal faults may pass downwards into a *detachment* or a *décollement* (Fig. 1). Although *rollover* was previously seen as proof of a listric geometry, normal faults with rollovers are now often interpreted as being planar (e.g. Roberts and Yielding, 1991, figs. 1 and 4). Listric geometries are commonly observed to occur within landslides, deltaic deposits and in much of the Basin and Range Province, USA (e.g. Beach and Trayner, 1991, fig. 2).

Membrane: A fault plane that is impermeable (e.g. Knipe, 1992).

Metamorphic core complex: A generally domal or arch-like uplift of deformed metamorphic and plutonic rocks overlain by tectonically detached and distended relatively un-metamorphosed cover rocks (Coney, 1980a,b). Origin and early usage of *metamorphic core complex* is discussed by Coney (1980a), while the distinction between *metamorphic complexes* and *mylonitic detachment complexes* is discussed by DeWitt (1980). The faults that exhume metamorphic core complexes typically have low to moderate dips, and may be normal faults (e.g. Crittenden et al., 1980; Dewey, 1988) or thrusts (e.g. Dallmeyer et al., 1992).

Net slip: See *slip*.

Network, fault: A system of linked and interacting faults, more diffuse than a *fault zone* (e.g. Stoces and White, 1935, fig. 327). When more than two fault sets are present, the network represents a triaxial strain system (Reches, 1983; Krantz, 1988).

Normal drag: Folding adjacent to a fault such that a marker is convex towards the slip direction, usually caused by resistance to slip (e.g. Hamblin, 1965; Biddle and Christie-Blick, 1985). See *reverse drag*.

Normal fault: A fault in which the *hanging wall* (rocks above the fault) is displaced downwards in relation to the *footwall*. The term originated in English coal-mining, where *normal* faults were met most commonly (e.g. Dennis, 1967).

Offset: The apparent *displacement* of a marker (e.g. Hobbs et al., 1976). Note, however, that *offset* has also been used synonymously with *overstep* (e.g. Segall and Pollard, 1980). We suggest that this latter usage should be avoided because of the more common use of *offset* for the apparent displacement of a marker.

Orogenic collapse: Gravity-induced extension of an orogenic belt, usually inferred to occur when compressional stresses are relaxed during or after a mountain-building event (e.g. Dewey, 1988).

Overlapping faults: Two sub-parallel, non-collinear faults with traces that partly extend past each other. *Overlap* is the distance between the ends of two *overstepping* faults, measured parallel to the faults (e.g. Rodgers, 1980). Synonymous with *jog*, *overstep* and *stepover*. Note, however, that *overlap* has a different meaning in sedimentology (e.g. Dennis, 1967).

Overstep: The area between two sub-parallel, non-collinear faults (e.g. Biddle and Christie-Blick, 1985). Synonymous with *jog* (Sibson, 1989), *offset*, *overlapping faults* and *stepover* (Aydin and Nur, 1982). Note that Butler (1982) defines *overstep propagation* of thrusts as the propagation of a family of thrusts in the direction opposed to the thrust transport direction, i.e. a new thrust develops in the *hanging wall* of an older thrust. *Overstep* has a different meaning in sedimentology (e.g. Biddle and Christie-Blick, 1985).

Overstep, along-strike: An *overstep* visible in map-view. For normal faults, an along-strike overstep is neither *contractional* nor *extensional*, and is marked by a *transfer zone* (e.g. Morley et al., 1990).

Overstep, contractional: An *overstep* that has to be accommodated by *contraction*, e.g. a right-step between sinistral faults. This type of overstep occurs in cross-section along normal faults, with the lower fault overstepping or projecting into the *hanging wall* of the upper fault (Peacock and Zhang, 1994) (Fig. 1). Synonymous with *anti-dilational jog* (Sibson, 1989), and with *compressional-*, *convergent-* and *restraining-overstep* (Biddle and Christie-Blick, 1985).

Overstep, extensional: An *overstep* that has to be accommodated by extension, e.g. a right-step between dextral faults. This type of overstep occurs in cross-section along normal faults, with the lower fault overstepping into the *footwall* of the upper fault (Peacock and Zhang, 1994) (Fig. 1). Synonymous with *dilational jog* (Sibson, 1989), and with *divergent-* and *releasing-overstep* (Biddle and Christie-Blick, 1985).

Palaeostress orientation analysis: Use of fault orientations and displacement directions of a population of faults to infer the orientations of the formative stresses (e.g. Angelier, 1984).

Permeability, fault: The ability of fluids to flow along or across faults (Smith, 1966; Morrow et al., 1984). Fault permeability can be anisotropic, with differences in flow perpendicular and parallel to a fault (e.g. Zhang and Tullis, 1998). See *seal*.

Polygonal faults: A network of faults with no regionally consistent preferred strike orientation. Polygonal normal faults have a similar appearance in map view to mud-cracks (e.g. Lonergan et al., 1998). Layer-bound polygonal faults in the North Sea are described by Cartwright and Lonergan (1996) and are attributed to vertical compaction.

Power-law: The relationship whereby $N \propto S^{-D}$, where N is the number in a population with a size greater than S, and D is the power-law exponent (e.g. Walsh and Watterson, 1992). Displacements for a population of faults have been shown to obey a power-law (Scholz and Cowie, 1990; Marrett and Allmendinger, 1992; Walsh and Watterson, 1992; Scholz et al., 1993). See *D-value* and *fractal*.

Process zone: Used in material science for an area of micro-cracking at the tip of a propagating fracture, involving non-linear behaviour. Process zones in rock are generally dilational areas (Atkinson, 1987, fig. 1.4). Process zones in normal fault zones are described by Cowie and Shipton (1998).

Propagation, fault: The increase in length, area and displacement of a fault or fault zone (e.g. Walsh and Watterson, 1987; Reches and Lockner, 1994; Peacock and Sanderson, 1996).

Pull-apart basin: A *basin* developed at an *extensional bend* or *extensional overstep* between two strike-slip faults (e.g. Burchfiel and Stewart, 1966; Crowell, 1974). They are generally approximately rhomb-shaped, with subsidence in the basin commonly controlled by normal faults (e.g. Crowell, 1974, fig. 3). Synonymous with *rhombochasm*, *rhombograben* and *sagpond*. *Pull-apart* has also been used for a rhomb-shaped area at an *extensional overstep* (e.g. Peacock and Sanderson, 1992; Peacock and Zhang, 1994) (synonymous with *domino* of Gamond, 1983) (Fig. 1). *Pull-aparts* can occur where normal faults are refracted to a steeper dip through more brittle beds.

Reactivation: Renewed displacement on a fault that has undergone a prolonged period of inactivity (e.g. Shephard-Thorn et al., 1972; Sibson, 1985); the fault has therefore been affected by two distinct tectonic events. The later displacement may or may not be of the same sense as the previous displacement. See *inversion* and *reverse-reactivation.*

Relay pattern: An arrangement of *overlapping* or *underlapping* sub-parallel faults (Harding and Lowell, 1979; Biddle and Christie-Blick, 1985, fig. 2). *Relay faults* are described by Goguel (1952).

Relay ramp: An area of reoriented bedding between two normal faults that overstep in map view and that have the same dip direction (Fig. 1). The faults may be *listric* and meet at depth (Larsen, 1988), approximately planar and unconnected at depth (Peacock and Sanderson, 1991), or may splay off the same approximately planar fault (Huggins et al., 1995). First called *relais des failles* (*relay faults*) by Goguel (1952, fig. 73). Synonymous with *strike ramp* (Morley, 1995, fig. 16), *synthetic accommodation zone* (Faulds and Varga, 1998) and with *synthetic transfer zone* (Morley et al., 1990).

Relay ramp, breached: A relay ramp that has been broken by one or more *connecting faults* (Childs et al., 1993) (Fig. 1).

Reverse drag: Folding adjacent to a fault plane such that a marker is concave towards the slip direction (Hamblin, 1965). An example is *roll-over* above a *listric* normal fault. First described by Dutton (1882), and synonymous with *downbending* and *turnover* (Hamblin, 1965).

Reverse-reactivation: The *reactivation* of a normal fault by a later episode of reverse displacement (e.g. Stoneley, 1982; Dart et al., 1995). See *inversion* and *reactivation.*

Rhomb block: Rhomb-shaped fault-bound block of rotated bedding resulting from the linkage of faults with zigzag traces (Morley, 1995, fig. 16). Similar to the *horse* shown by Ramsey and Huber (1987, fig. 23.50).

Rift: A relatively narrow trough or belt of subsidence bounded on either side by normal faults (e.g. Nelson et al., 1992). Rifts commonly contain or consist of *grabens* or *half-grabens.* Various usages (e.g. for structures on volcanoes) are described by Dennis (1967).

Rift valley: Defined by Gregory (1894) as a valley with steep parallel walls, formed by subsidence of a part of the Earth's crust.

Roll-over: Beds in the *hanging wall* that steepen towards a normal fault to form an anticline (e.g. Stoneley, 1982; Gibbs, 1984). *Roll-over* may indicate a *listric* geometry (e.g. Williams and Vann, 1987), or *reverse drag* around a planar fault (Barnett et al., 1987).

Rotation, horizontal-axis: Rotation of a fault block about a horizontal axis. Horizontal-axis rotation commonly accompanies normal faulting, for example during *bookshelf faulting* (e.g. Anders et al., 1993) and in *relay ramps* (e.g. Peacock and Sanderson, 1994, fig. 8). Synonymous with *tilting.*

Rotation, vertical-axis: Rotation of a fault block about a vertical axis. Vertical axis rotation commonly occurs in normal fault systems (e.g. Janecke et al., 1991), for example in *relay ramps* (Peacock and Sanderson, 1994, fig. 8).

Roughness, fault: A measure of the irregularity of a fault surface (e.g. Power and Tullis, 1991; Lee and Bruhn, 1996; Stewart, 1996).

Scale invariance: The property whereby a set of objects at one scale are geometrically identical to the set of objects when viewed at another scale (e.g. Turcotte, 1989; Main, 1996). The concept that faults have scale invariant geometries was introduced by Tchalenko (1970). See *fractal, self-affine* and *self-similar.*

Scaling relationship: The relationship between different-sized structures (e.g. Scholz and Cowie, 1990; Marrett and Allmendinger, 1992; Walsh and Watterson, 1992; Scholz et al., 1993). See *displacement–length ratio, D-value* and *power-law.*

Seal: A fault is *sealing* if fluid is unable to flow through the rock because the *fault rocks* are impermeable, or because of the geometry of the fault (e.g. Smith, 1966; Knott, 1993). See *fault juxtaposition diagram* and *smear.*

Segment, fault: An individual *slip plane* that is part of a set of sub-parallel faults that together form a *fault zone* (e.g. Segall and Pollard, 1980). Synonymous with *strand* (Biddle and Christie-Blick, 1985).

Self-affine: A set of objects or properties that exhibit *fractal* behaviour, but that show systematic changes in geometry with scale according to a linear transformation(s) (Mandlebrot, 1982; Gillespie et al., 1993). Self-affine objects are therefore not perfectly *self-similar.*

Self-similar: A set of objects or properties that exhibit *fractal* behaviour and that show *scale invariant* geometry at all scales (e.g. Turcotte, 1989; Main, 1996). Self-similarity of fault geometries was first illustrated by Tchalenko (1970). See *self-affine.*

Separation: The apparent displacement of a planar marker (e.g. bed) across a fault, measured in any indicated direction (Reid et al., 1913). Note, however, that *separation* has also been used for: (a) the distance between two *overstepping* faults, measured perpendicular to the fault planes (e.g. Rodgers, 1980); and (b) the distance between *overstepping* faults measured parallel to their strikes (Segall and Pollard, 1980) (synonymous with *overlap*). We suggest that these two latter uses should be avoided because *separation* is more commonly used for apparent displacement, with *overstep* and *overlap* being more suitable terms.

Slip: The distance between two formerly adjacent points on opposite walls of the fault, measured in a straight line on the fault surface (Reid et al., 1913). Synonymous with *net slip*, cf. *displacement*. Cowie and Shipton (1998) use *slip* synonymously with *slip event*.

Slip, cumulative: The finite displacements produced by a number of individual slip events on a fault (Walsh and Watterson, 1987).

Slip event: A single displacement event on a fault (e.g. Walsh and Watterson, 1987), i.e. associated with an earthquake (Cowie and Scholz, 1992b). The net slip and final displacement profile on a fault is usually the result of many slip events (Walsh and Watterson, 1987; Peacock and Sanderson, 1996).

Slip plane: Used in material science for a plane along which displacement may occur (e.g. Dennis, 1967). Used in geology for a surface along which displacement has occurred (e.g. Stewart and Hancock, 1991). Synonymous with *fault plane*.

Slip vector: The orientation and magnitude of the displacement of formerly adjacent points on opposite sides of a fault measured along the fault surface (Reid et al., 1913), cf. *displacement vector*.

Smear: Wall-rock material, usually clay-rich, spread along a fault surface (Perkins, 1961; Knipe, 1992; Knott, 1993; Lindsay et al., 1993). See *seal*.

Soft domino: Block rotation accommodated by ductile strain, including faults below the scale of the analysis (Gibson et al., 1989; Walsh and Watterson, 1991, fig. 10). This behaviour implies *geometric coherence*.

Soft-linkage: Coherence between faults achieved by ductile strain of the *wall-rocks*, i.e. there is no linkage by faults visible at the scale of observation (Walsh and Watterson, 1991). A *relay ramp* is an example of *soft-linkage*. See *hard-linkage* and *soft domino*.

Spacing, fault: The (average) distance between faults, usually measured in a line perpendicular to the fault plane or the fault strike. It only has a rigorous definition, therefore, for sets of sub-parallel faults, but may be applied to traverses perpendicular to the strike of conjugate normal fault sets. *Discontinuity spacing* is discussed by Priest and Hudson (1976, 1981). See *fault density*.

Splay, fault: One or more smaller faults that join a larger fault, to which it is related (e.g. Biddle and Christie-Blick, 1985, fig. 2). The larger fault *splays* if it is connected with one or more splay faults (DeSitter, 1956). See *branch*.

Stepover: Synonymous with *overstep* (Aydin and Nur, 1982).

Synthetic fault: Originally defined by Cloos (1928) as a minor fault that dips in the same direction as dipping beds. *Synthetic fault* is now used (e.g. Gibbs, 1984) for a minor fault that has the same displacement sense and a similar orientation to a related major fault, or the relationship whereby two related faults have the same shear sense. Two normal faults with downthrows to the north are *synthetic* to each other. See *antithetic* fault.

Synthetic transfer zone: Synonymous with *relay ramp* (Morley et al., 1990).

Tension fracture: Synonymous with *extension fracture* (e.g. McGrath and Davison, 1995).

Termination, fault: The end of a fault or fault zone, where displacement decreases to zero (e.g. Zhang et al., 1991). *Termination* has also been used for the location at which an earthquake rupture ends (e.g. Aki, 1989). See *damage zone* and *tip*.

Thermal subsidence and thermal uplift: Vertical movements related to thermal contraction and extension of the Earth's crust, respectively (e.g. Sleep, 1971; McKenzie, 1978; Roberts and Yielding, 1991).

Thickness, fault: The extent of the deformation and grain size reduction in a fault zone, usually measured perpendicular to the fault (Evans, 1990; Knott, 1994). *Gouge thickness* is defined by Byerlee and Summers (1976) as the thickness of crushed material between sliding surfaces. See *width, fault*.

Throw: The vertical component of the *dip-separation* of a normal or reverse fault, measured in a vertical cross-section perpendicular to the strike of a fault (e.g. Geikie, 1882; Hills, 1940; Billings, 1942) (Fig. 1). Throw is defined in terms of the *separation*, hence it applies to the faulted geometry of a plane and not the displacement (net slip) of the fault. The throw is equivalent to the vertical component of the *displacement* only for a pure *dip-slip* fault. See *heave*.

Tilting: Rotation of a fault block about a horizontal axis. Tilting commonly accompanies normal faulting (e.g. Anders et al., 1993), for example in *relay ramps* (Peacock and Sanderson, 1994, fig. 8). Synonymous with *horizontal axis rotation*.

Tip: A *tip point* is a site where fault displacement dies to zero, e.g. where a fault trace ends on a map (e.g. Coward and Potts, 1983) (Fig. 1). A *tip line* is the line around a fault plane where displacement becomes zero. Barnett et al. (1987) suggest that *isolated* normal faults have elliptical tip lines. A *tip zone* is an area of *damage* at the termination of a fault. Synonymous with *fault termination*.

Transfer fault: A fault that links, is at a high angle to, and that transfers displacement between two normal faults (Gibbs, 1984, fig. 15) (Fig. 1). Transfer faults between normal faults in map view usually have a significant strike-slip component (Stewart and Hancock, 1991). *Transfer fault* is approximately synonymous with *transform fault* (Bally, 1981, fig. 2) and with *cross-strike fault* (Morley, 1995, fig. 16).

Transfer zone: Dahlstrom (1970) uses *transfer zone* for the structures that conserve shortening, or allow a regular change in shortening, between overstepping thrust faults. *Transfer zone* is also used for an area of deformation and bed rotation between two normal faults that overstep in map view (Fig. 1). Morley (1995) suggests that the faults which define a transfer zone were active at the same time, in contrast to *accommodation zone*, in which the two faults need not have been active at the same time (Bosworth, 1985). Morley et al. (1990, fig. 1) describe *synthetic transfer zones* and *conjugate transfer zones*, in which the overstepping faults dip in the same and opposite directions, respectively. Conjugate transfer zones can be further sub-divided into *convergent-* and *divergent-*transfer zones (Morley et al., 1990). See *relay ramp*. Faulds and Varga (1998) discuss previous usage of *transfer zone* and *accommodation zone*. They redefine a *transfer zone* as a discrete zone of strike-slip and oblique-slip faulting that typically transfers strain between en échelon extended domains, and define an *accommodation zone* as a belt of overlapping fault terminations (Faulds and Varga, 1998, figs. 4, 5 and 6, table 1). We suggest that these definitions are unhelpful because: (a) they are redefinitions of existing terms; and (b) the distinction between the two types of zone may be arbitrary (e.g. an *accommodation zone* can contain elements of a *transfer zone*, with strike-slip faults developing as the zone becomes *breached*).

Transtension: A system of stresses that tends to cause oblique-extension, i.e. combined extension and strike-slip (e.g. Harland, 1971; Sanderson and Marchini, 1984).

Underlapping faults: Two faults that *overstep* such that they do not pass each other, i.e. a line can be drawn between and perpendicular to the faults that does not cross either fault (e.g. Pollard and Aydin, 1984). See *overlap*.

Wall-rock: Old mining term for the country rock bounding a vein, now commonly used for the rocks surrounding and displaced by a fault (see Dennis, 1967).

Width, fault: The term has two uses. (a) *Fault width* is often used for the thickness of fault rock along a fault plane (e.g. Knott, 1994; Caine et al., 1996). Synonymous terms including *fault-rock width* and *fault thickness*. (b) Barnett et al. (1987) and Walsh and Watterson (1988) use *fault width* for the major axis of a fault plane, that is usually along the strike of a normal fault. We suggest that this latter usage should be avoided because it is less intuitive than *fault length*, which is used by some other authors (e.g. Scholz and Cowie, 1990) for the trace length or for the major axis of the fault plane.

Zone, fault: Defined by Hills (1940) as the zone of disturbed rocks between faulted blocks. Now commonly used for a system of related fault *segments* that interact and link, and are restricted to a relatively narrow band or volume (e.g. Nevin, 1931; Peacock and Sanderson, 1991). A fault zone can include fault segments with a wide range of orientations, and these can be both *synthetic* and *antithetic* to the overall displacement of the zone.

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