The relationship between displacement and length of faults: a review

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Received 22 September 2003; accepted 22 June 2004

Abstract

The relationship between maximum displacement ($d_{\text{max}}$) and fault length ($L$) has been studied extensively, mainly in attempts to understand how fault geometry varies over different length scales. Individual data sets are sampled over limited length scales, and values of $d_{\text{max}}$ and $L$ are generally poorly correlated, thus relationships are usually postulated on the basis of combining different data sets. There are problems in sampling both $d_{\text{max}}$ and $L$ in a consistent manner over these different length scales, especially where different data collection methods are used (e.g., field and seismic reflection data).

Failure to resolve low-displacement tips and damage zones leads to underestimates of $L$, and exclusion of fault drag leads to underestimates of $d_{\text{max}}$. Measurement of non-central fault traces leads to underestimates of both $d_{\text{max}}$ and $L$ and an underestimate of $d_{\text{max}}/L$. In this paper, we examine factors that control the measured displacement–fault length relationships of natural faults. We suggest that there may be systematic differences between the $d_{\text{max}}/L$ ratios where length is measured parallel or normal to the displacement vector, and where the growth histories of individual faults vary due to the nature and number of slip events, linkage, and reactivation. Controlling factors also include material properties and fault types. It is explained how each controlling factor contributes to the $d_{\text{max}}/L$ ratio and should be considered in the statistical analysis of fault data.

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Keywords: Fault length; Maximum displacement; Linkage; Propagation; Scaling; Damage; Reactivation

1. Introduction

It has been widely recognized that fault displacement varies within the fault surface (e.g., Barnett et al., 1987). Displacement is zero at the fault tips and usually increases to a maximum near the centre of the fault surface (Fig. 1). Fault size has been measured in different ways, usually as either the maximum displacement ($d_{\text{max}}$) or the maximum dimensions, such as length ($L$) or height ($H$) of an individual fault surface (e.g., Walsh et al., 2003a). These concepts may be applied to either the fault surface or to fault traces on topographic surfaces, cross-sections, or...
geological horizons. Many researchers (e.g., Watters-
son, 1986; Walsh and Watterson, 1988; Marrett and
Allmendinger, 1991; Gillespie et al., 1992; Cowie
and Scholz, 1992a,b; Dawers et al., 1993; Scholz et al.,
1993; Clark and Cox, 1996; Schlische et al., 1996)
have proposed relationships between these geometric
elements.

Studies of fault displacement profiles (e.g., Mur-
aoka and Kamata, 1983; Peacock and Sanderson,
1991; Kim et al., 2000; 2001a) have been used to
provide insights into the propagation and slip history
of faults, and hence their growth and evolution (e.g.,
Walsh and Watterson, 1987, 1988; Cowie and Scholz,
1992a,b; Dawers et al., 1993; Peacock et al.,
1996; Schultz, 2000; Kim et al., 2001a,b; Wilkins
and Gross, 2002). The development of an accurate
three-dimensional (3-D) model for the accumulation
of displacement on faults is needed to aid prediction
of the displacement geometries (Peacock, 2002).

2. Factors affecting measurement of fault length

In 3-D studies, the size of a fault can be specified
by its surface area, but to represent fault shape and in
2-D studies measures of fault length are commonly
used. The term ‘fault length’ has not been consistently
defined in the literature, and measurement of ‘length’
is subject to various sampling constraints.

2.1. Position and direction of measurement

Fault length is generally defined in one of two
ways.

(1) As the ‘length measured in a direction parallel to
the slip vector’ (e.g., Watterson, 1986; Walsh
and Watterson, 1988) with the length normal to
the slip vector within the slip plane being
referred to as the ‘fault width’ (Watterson, 1986).

(2) As the ‘trace length in map view’ or ‘the longest
horizontal dimension’ (e.g., Dawers et al., 1993;
Cartwright et al., 1995; Willemse et al., 1996;
Poulimenos, 2000; Schultz and Fossen, 2002). Lengths measured in the dip direction are usually referred to as the ‘fault height’ or ‘cross-sectional trace length’ (Wilkins and Gross, 2002).

We propose a unified terminology for fault description that can be applied consistently to all faults irrespective of their kinematics. Fault length \( L \) is the longest horizontal or subhorizontal dimension along the fault plane, and fault trace length \( L' \) is the exposed fault length on an arbitrary (sub)horizontal plane (Fig. 1). Fault height \( H \) is the longest dimension of the fault plane measured in cross-section normal to strike, and fault trace height \( H' \) is the exposed length in cross-section. We reserve the use of the term ‘width’ for measures of fault zone thickness. These definitions are thus independent of the orientation of the slip vector and conform to the definitions most widely used by researchers.

Basically, our suggested terminology is similar to that of Willemse et al. (1996, fig. 1). However, if the largest dimension of the fault is not horizontal, it is very difficult to express the length and height based on their definitions.

Walsh and Watterson (1988) introduced the term fault radius \( R \) to refer to “half” of the fault length (or height). This concept is easy to apply where it is possible to measure the distance from the position of maximum displacement to one of the fault tips. For a reasonably symmetrical displacement profile, with the \( d_{\text{max}} \) near the centre of the fault, fault radius is approximately half of the fault length \( R \approx L/2 \).

Recently, high-resolution 3-D seismic data, mainly from hydrocarbon exploration, have been widely used for fault analysis (e.g., Childs et al., 1995; Nicol et al., 1996; Dorn, 1998; Story et al., 2000; Childs et al., 2003). The proposed terminology is easily applied to such data, where the 3-D fault geometry can be almost completely viewed and understood, but there is no direct indication of fault slip or kinematics.

Where the slip direction is known or the type of fault identified (i.e., normal, thrust, or strike–slip), it may be possible to measure the maximum length or trace length of the fault in the slip direction \( U \). In strike–slip faults, the exposed trace length in map view is usually measured as fault length (i.e., \( L = U \)), but in normal and thrust faults, the cross-sectional trace length \( (H = U) \) or the trace length in map view \( (L = U) \) may be measured and both expressed as fault length. Sometimes, the measured fault length is not clearly defined in the literature.

Cowie and Scholz (1992b) argue that large faults are essentially 2-D, being confined to the brittle upper crust and only free to propagate at their lateral ends, whereas small faults are 3-D and may propagate along their entire perimeter. This means that the ‘trace length in map view’ is usually much larger than the ‘cross-sectional trace length’ in larger faults.

Schultz and Fossen (2002) have pointed out that displacement will depend on both the length \( L \) and height \( H \) of the fault (Fig. 1), and hence on the aspect ratio of the fault surface. They derive expressions for \( d_{\text{max}}/L \) ratios, which suggest that elliptical faults will accommodate less displacement where aspect ratios increase with length compared to populations of faults with constant aspect ratio. This will happen when fault height is constrained by layering (on any scale). Such faults would not be expected to show displacements proportional to fault length, and where \( L > > H \) will have shallow (<1) slopes on log/log plots of \( d_{\text{max}}/\text{against L} \). This is not seen in the compilation of natural data (Fig. 5), where, if anything, larger faults have higher \( d_{\text{max}}/L \).

### 2.2. Seismic resolution and “missing fault tips”

Many sampling methods will only resolve faults above some limit. In the case of commercial 3-D seismic data, this may be at displacements of 10 m or more. It therefore follows that only parts of faults above this limit will be observed and that true fault length will be undersampled (Fig. 2a). Assuming a linear displacement gradient (of the type shown in Fig. 2a), the true \( d_{\text{max}}/L \) value is related to the observed value as follows:

\[
\frac{d_{\text{max}}}{L_{\text{true}}} = \frac{(d_{\text{max}} - r)}{L_{\text{obs}}},
\]

where \( r \) is the resolution limit of the fault displacement. The effect on the \( d_{\text{max}}/L \) plot is shown on Fig. 2b for a range of typical \( d_{\text{max}}/L \) ratios. With a lower resolution of throw of 10 m, Pickering et al.
argue that fault length may be underestimated by 250–1000 m, and hence faults with observed lengths of less than a few kilometers are significantly underestimated. Other forms of fault data may be subject to similar resolution effects. Walsh and Watterson (1988) recognized that the faults represented on coal mine plans were generally only resolved where displacement was "significant" in mining terms (for throws of >100 mm and fault length by about 50 m). Therefore, account must be taken of the poor resolution at fault tips where displacements are low.

2.3. Inclusion or exclusion of damage zones

Damage zones around faults (e.g., Peacock, 2002; Kim et al., 2003, 2004) play two important roles in evaluating $d_{\text{max}}/L$ relationships. First, damage zones, especially at fault tips, and linkage zones complicate the displacement–distance profiles (Peacock and Sanderson, 1991; Kim et al., 2000, 2001b). They generally represent regions that accommodate displacement or enhanced displacement gradients, and thus are important in the interpretation of $d_{\text{max}}/L$ relationships. Second, the damage zone may form part of the fault length, and as such should be included in the measure of fault length ($L$).

Recently, Kim et al. (2003) have suggested 3-D fault tip-damage model around an elliptical fault. Just as there is a correlation between the fault core width and displacement (e.g., Hull, 1988; Evans, 1990), there is also increasing realization that the size of the damage zone may correlate with displacement (e.g., Knott et al., 1996; Shipton and Cowie, 2001). The fault damage zone area is the area needed to cover the secondary faults and tip fractures associated with the faults (Fig. 3a). For this plot, we only considered strike–slip faults and mode II fault tip-damage zones (see Kim et al., 2003, 2004). Fig. 3b is a log–log plot of the square of fault length versus damage zone area for 12 strike–slip faults from well-documented examples in the literature and from new outcrops. The faults range from several tens of centimeters to several hundred kilometers and show a good correlation between fault length and total damage zone area. Damage zone area is proportional to the square of the fault length; hence, the linear dimension (nominal diameter) is proportional to fault length.

3. Factors affecting measurement of fault displacement

Observational and theoretical considerations suggest that displacements are distributed in three dimensions across a bounded fault surface (Walsh and
Watterson, 1987, 1988; Childs et al., 1995; Willemse et al., 1996; Schultz and Fossen, 2002). However, the 2-D nature of many data sets yield an estimate of $d_{\text{max}}$ along a fault trace. Wilkins and Gross (2002) argue that $d_{\text{max}}$ for fault traces would be expected to scale with trace length ($L$) when measured in both the strike and dip directions, although the two maximum displacements may not be the same. Although most authors discuss the relationship of fault displacement to length, much of the data actually refer to fault separation. Displacement is the relative movement between two originally adjacent points on the surface of a fault, whereas separation is the distance between the traces of two planar markers across a fault. For normal faults, the vertical separation or throw is most commonly determined especially from seismic sections (e.g., Walsh and Watterson, 1988; Peacock and Sanderson, 1991). For thrust faults, displacement is usually determined from dip separation or horizontal separation, and with low dips, these values should be similar. For strike–slip faults, displacement is usually estimated from horizontal separation, ideally of steeply inclined features or properly determined piercing points. The main source of error will come from attempting to use lateral (or horizontal) separations based on features at a low angle to the slip vector, as will occur with shallowly dipping features in a strike–slip system, or where the slip vector may contain both large dip–slip and strike–slip components.

3.1. Cut effect

Maximum displacement is generally located and measured around the fault centre. However, an arbitrary section through a fault will not generally cut the fault centre, and even if it were to, this would not be recognizable. Therefore, a fault must be analysed from its exposed fault trace, whose length will generally be less than the maximum length, and the maximum displacement on this trace will also generally be less than that for the whole fault surface. Walsh and Watterson (1988) recognized this aspect in their analysis of fault trace data. Assuming the fault...
surface is elliptical with an aspect ratio $L/H$ and that displacement varies linearly with distance from the fault centre (Fig. 4a), then

$$d^* = (1 - x)d_{\text{max}}$$  \hspace{1cm} (2a)

$$L' = (1 - x^2)^{1/2}L$$  \hspace{1cm} (2b)

Thus

$$d^*/L' = [(1 - x)/(1 + x)]^{1/2}d_{\text{max}}/L$$  \hspace{1cm} (3)

The results of this “cut effect” are shown on Fig. 4b for three faults of maximum length 10,000 m and maximum displacements of 1000, 300, and 100 m at values of $x$=0.05, 0.15, $\ldots$, 0.95. Most arbitrary sections will be within 50% of the value of $d_{\text{max}}/L$, but some will be much less and the ‘tail’ lies on a line of $d/L$ with a slope of about 2 on the log/log plot (see also Walsh and Watterson, 1988). Putting $x=0.95$ in Eq. (3) gives $d^*/L' = 0.16d_{\text{max}}/L$, indicating a 5% chance of observed $d/L$ ratios being almost one-sixth of magnitude lower than the true value. For any sample of faults with a range of lengths, the cut effect will tend to ‘smear’ the $d_{\text{max}}$ values over about one order of magnitude, and if the range of lengths is small, may steepen the slope ($n$) on the log/log plot.

3.2. Fault drag and bed rotation

Ductile drag can modify displacement values obtained from separation of strata. Walsh et al. (1996) demonstrate ductile strain effects in the analysis of seismic interpretations of normal faults that include (i) extension in an array of subseismic normal faults, (ii) ductile shear strain in a relay zone, (iii) a zone of ductile strain in an intersection zone between conjugate normal faults, and (iv) ductile displacement and ductile bed extension in a hanging wall fold.

Large displacement gradients in relay zones are generally accommodated by bed rotations or drag folds (Peacock and Sanderson, 1991; Anders and Schlische, 1994; Nicol et al., 2002). Indeed relay zones and tip line folds may be identified from differences in bed geometry and fault displacement distribution (Nicol et al., 2002).

Displacement–distance plots (e.g., Muraoka and Kamata, 1983; Peacock, 1991; Nicol et al., 2002) have been used to assess the kinematic relationship between faulting and folding. For example, Nicol et al. (2002) show that a decrease in fault displacement within relay zones may be accommodated by increased bed rotation and folding. They suggest that aggregate displacement profiles are less variable than separate plots of discontinuous and continuous components of deformation, suggesting that faults and fold may be kinematically coherent.

In general, normal drag would be expected to reduce the displacement measured from separation...
of strata across the fault, and the effect on different data sets needs to be appreciated when compiling $d_{\text{max}}/L$ plots. For example, Gross et al. (1997) suggest ‘frictional drag’ may decrease the $d_{\text{max}}/L$ ratio adjacent to larger faults. More commonly, such drag may be localized close to the fault plane and be included in displacement estimates from seismic profiles but excluded from measurement of stratigraphic separation from field studies.

4. General relationship between maximum displacement ($d_{\text{max}}$) and fault length ($L$)

It is generally assumed that the relationship between the maximum cumulative displacement on a fault ($d_{\text{max}}$) and the maximum linear dimension of the fault surface ($L$ or $H$) is of the form:

$$d_{\text{max}} = c L^n,$$

(4)

The range of the exponent value, $n$, is from 0.5 to 2.0 ($n=2.0$, Watterson, 1986; Walsh and Watterson, 1988; $n=1.5$, Marrett and Allmendinger, 1991; Gillespie et al., 1992; $n=1$, Cowie and Scholz, 1992a,b; Dawers et al., 1993; Scholz et al., 1993; Clark and Cox, 1996; Schlische et al., 1996; $n=0.5$, Fossen and Hesthammer, 1997). The value of the exponent, $n$, is important as $n=1$ indicates a linear scaling law (i.e., self-similarity), and $n \neq 1$ is a scale-dependent geometry. The value of $c$ is an expression of fault displacement at unit length. For a linear scaling (i.e., $n=1$), $c$ is simply the ratio $d_{\text{max}}/L$.

A lot of fault data have been collected and analysed (e.g., McMillan, 1975; Elliott, 1976; Muraoka and Kamata, 1983; Walsh and Watterson, 1987; Krantz, 1988; Opheim and Gudmundsson, 1989; Peacock and Sanderson, 1991; Dawers et al., 1993; Vilemin et al., 1995; Schlische et al., 1996; Wilkins and Gross, 2002). Because of the different sampling constraints, we have separated the data for normal, thrust, and strike–slip faults (Fig. 5).

Each individual data set may be subject to various combinations of the measurement error discussed in Sections 2 and 3. In comparing different data sets, one must bear in mind these underlying sampling effects and recognize that the tectonic setting, history, and host lithology of the faults may be very different.

5. Factors controlling the ratio of maximum displacement ($d_{\text{max}}$) and fault length ($L$)

There are several factors that control $d_{\text{max}}/L$, such as (1) material property, (2) type of fault including position and direction of measurement, (3) earthquake rupture and slip/propagation history, (4) segmentation and linkage (evolution), and (5) reactivation.

Field studies (Rippon, 1985; Wilkins and Gross, 2002) as well as numerical models (Burbmann et al., 1994) suggest that differences in mechanical properties and contacts between adjacent lithologic units can create effective barriers that inhibit fault propagation in small-scale faults. Steen and Andresen (1999) show the effect of lithology on fault scaling, and Wilkins and Gross (2002) show that displacements may be affected when faults pass through lithologic boundaries. However, we can determine no systematic trend in the graphs (Fig. 5), and this may indicate that layering may produce variation in $d_{\text{max}}/L$ ratio at small-scales but is not so effective at larger scales.

Comparing different fault types, the $d_{\text{max}}/L$ ratio for strike–slip faults (Fig. 5c) is slightly higher than for dip–slip faults, i.e., thrusts (Fig. 5b) and normal faults (Fig. 5a). The higher $d_{\text{max}}/L$ ratios of strike–slip faults might be due to the fault length being measured parallel to the slip direction.

It has also been argued that the $d_{\text{max}}/L$ ratios are different depending on fault scale, with larger faults having proportionately larger displacements (e.g., Clark and Cox, 1996; Kim et al., 2000). Other workers (e.g., Scholz and Cowie, 1990; Dawers et al., 1993) support a scale-invariant displacement distribution. Some effect of the difference may be because large faults are 2-D, constrained at their lateral ends, whereas small faults are 3-D, pinned along their entire perimeter (Sibson, 1989; Cowie and Scholz, 1992b).

Fig. 5 shows that $d_{\text{max}}/L$ ratios may increase slightly with increasing fault length. This might be due to different fault growth mechanisms at different scales, with greater mechanical interaction and strain localization on larger faults (e.g., Cowie and Scholz, 1992b; Willemse et al., 1996; Walsh et al., 2002, 2003b).
6. Fault growth models and $d_{\text{max}}/L$ plots

Two conceptual models for fault initiation and growth have widely been accepted. According to the first model, a fault is a single smooth continuous surface of displacement discontinuity, which becomes larger as the slip increases (e.g., Watterson, 1986; Walsh and Watterson, 1987, 1988; Marrett and Allmendinger, 1991; Cowie and Scholz, 1992a,b). According to the second concept, faults grow primarily by the linkage of individual segments (e.g., Segall and Pollard, 1980; Ellis and Dunlap, 1988; Martel et al., 1988; Peacock and Sanderson, 1991; Cartwright et al., 1995; Kim et al., 2000).

6.1. Earthquake rupture and single-slip events

Studies of earthquakes show that magnitude and seismic moment are related to the slip and the dimensions of the rupture, as estimated from the extent of surface deformation, dimensions of the aftershock zone, or earthquake source time functions (Utsu and Seki, 1954; Utsu, 1969; Kanamori and Anderson, 1975; Wyss, 1979; Singh et al., 1980; Purcaru and

Fig. 5. Plots of maximum displacement ($d_{\text{max}}$) against fault length ($L$). (a) normal faults, (b) thrust faults, and (c) strike-slip faults. SS, sandstone; LS, limestone; SH, shale.
An empirical relationship between the maximum slip on a rupture \( (u) \) and the surface rupture length of the fault \( (L_S) \) is given as (Fig. 6; Wells and Coppersmith, 1994):

\[
\log(u) = -1.38 + 1.02 \times \log(L_S)
\]  

Subdividing the data according to slip sense, tectonic settings, or geographic region may provide slightly different results but does not significantly modify the correlations (Wells and Coppersmith, 1994). Typical ratios of \( u/L_S \) for seismic ruptures are in the range \( 10^{-5} - 10^{-4} \) compared to \( d_{\text{max}}/L \) ratios of \( 10^{-2} - 10^{-1} \) for geological faults. This suggests that faults represent many \((\sim 10^3)\) slip events. Single-slip events usually rupture only part of the fault surface, with large faults such as the San Andreas Fault or North Anatolian Fault rarely rupturing >10\% of their fault surface (see Fig. 5c).

6.2. Growth of a single fault

Faults grow through the accumulation of slip, often associated with earthquake events that may
involve increasing displacement and/or length (e.g., Walsh and Watterson, 1987; Cowie and Scholz, 1992a,b; Bürgmann et al., 1994). As the fault develops, a slip may occur on individual segments or groups of segments, not all of which will increase the length of the fault system as a whole. Thus, as the number of events increases, the displacement–distance profile and the ratio of $d_{\text{max}}/L$ will depend on the distribution of these events and the rate of fault propagation (Peacock and Sanderson, 1996).

Filbrandt et al. (1994) demonstrate that $d_{\text{max}}/L$ ratios change significantly during the early stages of fault growth (Fig. 7b), and Gross et al. (1997) reported that in contrast to small faults, displacement on large faults is independent of fault length. Walsh et al. (2002) suggest an alternative fault growth model (Fig. 7c), in which fault length is established rapidly producing essentially constant lengths for much of the duration of faulting. They argue that a progressive increase in displacement–length ratio could reflect fault system maturity (Walsh et al., 2002). Their model predicts that many faults should plot vertically between earthquake rupture data line ($\sim 10^{-3}$) and natural fault data line without increase in fault length (figure 1 in Walsh et al., 2002).
In Fig. 7, several fault growth models are illustrated. Fig. 7a is a ‘constant $d_{\text{max}}/L$ ratio model’ that is usually applied for small, isolated faults. Fig. 7b is an ‘increasing $d_{\text{max}}/L$ ratio model’, in which the $d_{\text{max}}/L$ ratio increases with fault growth. Fig. 7c is the ‘constant length model’ suggested by Walsh et al. (2002), in which the fault length is attained rapidly at an early stage and remains unchanged as displacement increases. Fig. 7d is the ‘fault linkage model’ (Peacock and Sanderson, 1991; Cartwright et al., 1995; Kim et al., 2000), in which the faults grow as isolated faults at early stages and then link to produce additional fault length. Thereafter, the fault may evolve by any of the models.

6.3. Segmentation and linkage

Segment linkage has been proposed as an important mechanism for fault growth (Peacock, 1991; Peacock and Sanderson, 1991; Cartwright et al., 1995; Willems et al., 1996; Kim et al., 2000, 2001b; Wilkins and Gross, 2002). Three stages can be identified in the growth of linked fault segments (Fig. 8a; Peacock and Sanderson, 1991). Initially isolated faults (stage 1) can propagate towards each other. Eventually, the fault tips approach one another and interact. The fault segments may evolve without obvious connection (soft linkage—stage 2) or link by breaching the relay zone (hard linkage—stage 3). The soft-linked seg-

![Image of fault growth models](image_url)
ment faults grow by interacting with adjacent faults which inhibits propagation, and thus, they attain high $d_{\text{max}}/L$ ratios. Hard linkage suddenly increases fault length (Fig. 7d); thereafter, the linked segments rapidly accumulate displacement rather than length (steep slope, stage 3).

Fig. 8 shows block diagrams, displacement profiles, and $d_{\text{max}}/L$ plots for the schematic growth of a strike–slip fault during segment interaction and linkage. The maximum displacement ($d_{\text{max}}$)–fault length ($L$) relationship evolves from isolated faults through segmented faults to interacting faults with a step-like route in one of two ways. Either the soft-linked segments build up displacement with restricted propagation, producing higher $d_{\text{max}}/L$ ratios (e.g., Willemse et al., 1996), or early hard linkage increases fault length, prior to continued build up of displacement. Repeated linkage of segmented faults may produce a step-like growth path (Fig. 8c; Cartwright et al., 1995; Kim et al., 2000). The lowest $d_{\text{max}}/L$ ratios occur at stage 2, where segments have just connected (Fig. 8c), with higher ratios occurring for isolated faults and at the mature stage of linked faults (Fig. 8c).
The displacement–distance profiles for multisegmented faults may show displacement minima at segment offsets (Fig. 8b, stage 2; Peacock and Sanderson, 1991). Walsh et al. (2003a) suggest a 'coherent fault model', in which individual fault segments initiate and grow as kinematically related components of a fault array by fault surface bifurcation, i.e., splaying out of the single fault plane. In this model, plots of $d_{\text{max}}$ against $L$ may be scattered, with data derived from the whole fault length or segments depending on the degree of observed linkage (Fig. 9). For both normal and strike–slip faults, the average $d_{\text{max}}/L$ for individual segments is generally larger than $d_{\text{max}}/L$ for the fault zone as a whole (Peacock and Sanderson, 1991; Vermilye and Scholz, 1995).

6.4. Reverse reactivation (or inversion)

Some faults experience reactivation with the opposite sense of slip in response to changing stress conditions or tectonic settings (e.g., Kelly et al., 1999; Kim et al., 2001a). These reverse-reactivated faults may show lower ratios of $d_{\text{max}}/L$, because fault length may increase whilst net fault displacement is reduced (Kim et al., 2001a). During fault reactivation, the change of displacement and length is schematically illustrated in Fig. 10. The arrows indicate supposed fault evolution paths (Fig. 10a).

The maximum displacement ($d_{\text{max}}$) and fault length ($L$) for five faults showing evidence of initial dextral slip followed by sinistral reactivation from Crackington Haven are plotted in Fig. 10a (Kim et al., 2001a). The four faults with net dextral slip have $d_{\text{max}}/L$ ratios of $10^{-2}$–$10^{-1}$, which is similar to faults showing no reactivation (Kim et al., 2000). Faults A and B, showing relatively weak reactivation, have higher $d_{\text{max}}/L$ ratios, whereas faults C and D have more reverse reactivation and lower $d_{\text{max}}/L$ ratios. Fault E, which initiated as a dextral fault but has net sinistral slip, plots with a relative low $d_{\text{max}}/L$ ($<10^{-2}$).

Although the displacement gradient during reactivation is not known, they may be estimated from the extended fault tips (10% to 20% of original fault length in this case), and is about $d_{\text{max}}/L = 0.025$ in this case. This implies that the ratio of $d_{\text{max}}/L$ decreases with progressive reactivation as shown in Fig. 10a, b, and d. For faults such as E, which have little early dextral displacement, the evolution may be along the path $d_{\text{max}}/L \approx 0.005$ (Fig. 10a), with reactivation producing a net sinistral slip as in Fig. 10a, c, and d.

![Fig. 9. Segmented fault array in the Bishop Tuff, California, showing a systematic distribution of throw along seven fault segments (solid lines). The aggregate throw profile is shown as dashed lines, but this does not include the strain accommodated by the rotation of bedding with the relays zones. Reproduced from Willemse (1997).](image-url)
Fault reactivation is a key factor in modifying fault displacement geometries and in controlling the pattern of deformation (e.g., Allmendinger et al., 1987; Jackson, 1987; McClay, 1989; Williams et al., 1989; Kim et al., 2001a; Walsh et al., 2002). For a population of existing faults, reactivation will not affect all orientations or scales of faults equally (Kelly et al., 1999) but tend to select faults in optimal condition for reactivation. In faults that are reactivated with opposite sense of slip, the net displacement is reduced as propagation continues, resulting in the ratio of \( \frac{d_{\text{max}}}{L} \) becoming lower.

### 7. Conclusions

1. A general relationship exists between maximum displacement \( (d_{\text{max}}) \) and fault length \( (L) \) over many orders of magnitude. This relationship is of the form \( d_{\text{max}} = cL^n \). Where the exponent \( n = 1 \), as is often observed, then \( d_{\text{max}} \propto L \) and fault populations may be characterized by their \( \frac{d_{\text{max}}}{L} \) ratios.

2. There is variation in the use of the terms length, height, and width of faults, and a rational descriptive system is proposed. Fault length is measured (sub) parallel to strike, and height is measured (sub) parallel to dip.

3. Considerable variation exists in \( \frac{d_{\text{max}}}{L} \) ratios of faults. As sampling constraints generally limit the range of fault lengths, correlations between the \( d_{\text{max}} \) and \( L \) are often poor for individual data sets, and relationships are usually based on comparison of different data sets. Care needs to be taken when combining and comparing different data sets that may be based on different measurement techniques.

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Fig. 10. A simple conceptual model for displacement and distance relationship of reactivated strike–slip faults at Crackington Haven. (a) The evolution of \( d_{\text{max}}/L \) during reactivation on normal plot. Two reference lines are drawn from average \( d_{\text{max}}/L \) of interacting faults and isolated faults at Crackington Haven. (b) Two stages of fault displacement along a fault. It shows negative displacement at the tip zones. Stage 1 shows dextral movement and stage 2 shows sinistral movement along the preexisting fault plane. (c) The total displacement profile after the final stage. (d) \( d_{\text{max}}/L \) evolution during reactivation for the two cases. Dextral displacement is dedicated as positive sign (+), and sinistral is dedicated as negative sign (−) (after Kim et al., 2001a).
(4) Some measurement methods lead to the systematic underestimation of the maximum fault length. Reasons include measurement of non-central fault traces and failure to resolve low-displacement tips and damage zones. The size of the damage area is shown to correlate with fault length.

(5) Maximum fault displacement may be underestimated due to the measurement of non-central fault traces and exclusion of fault drag. Many published studies are based on some measure of separation (often throw), and where fault kinematics is poorly constrained, these separations may differ significantly from displacements.

(6) There is some evidence that \( d_{\text{max}}/L \) ratios are higher for strike-slip than dip-slip faults. This may reflect, at least in part, the parallelism of the measured length with the slip direction. The ratio of \( d_{\text{max}}/L \) also depends on mechanical factors, such as frictional tips and the elastic modulus of the wall rocks.

(7) Most geological faults have a much higher ratio of \( d_{\text{max}}/L \), generally \( >10^{-3} \), than for single earthquake slip events, where the ratio of slip to rupture length is generally \( <10^{-4} \). Accumulation of successive earthquake slip events produces total displacement, and the number, distribution, and magnitude of slip events control the \( d_{\text{max}}/L \) ratio.

(8) The ratios between maximum displacement \( (d_{\text{max}}) \) and fault length \( (L) \) may change during the evolution of a fault. The \( d_{\text{max}}/L \) ratio is high for interacting segments and mature linked faults but may be low at the stage of linkage. Combining data from faults at these different stages of development may contribute to the scatter in \( d_{\text{max}}/L \) plots.

(9) Faults usually have experienced long and complex histories, and displacements can be accumulated or reduced by subsequent movement events. Reactivation with the opposite sense of displacement has been shown to reduce the \( d_{\text{max}}/L \) ratio.

Acknowledgement

We thank Giuliano Panza, John Walsh, Haakon Fossen, and David Peacock for their constructive comments. We also thank C.Y. Ryoo for introducing us to some excellent outcrops, and J.Y. Park and S.I. Park for their help with statistical processing. Encouragement to publish this work by J.H. Kim, and BK21, SEES, SNU are also appreciated. The fieldwork is partly funded by the MOCIE project of the Korean government (R-2002-0-279).

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