Reports

Role of Fault Bends in the Initiation and Termination of Earthquake Rupture

Abstract. *Rupture in individual earthquakes apparently is limited to regions between bends in faults. This is illustrated for eight events that have occurred since 1966. A model based on geometric concepts describes why this is so and clarifies earlier ideas of "asperities" and "barriers" used to explain earthquake initiation and termination processes. Because of their importance in the rupture process, bend zones should be monitored for precursory effects.*

A number of investigators have commented on the relation between changes of fault strike and processes of earthquake rupture (*1–7*). In this report we emphasize the generality of their observations, using eight recent earthquakes as illustrations. Six are strike-slip faulting, and two are reverse faulting. Reliable information about both the initiation and the termination processes is available only in some cases, but we know of no earthquake for which the lateral extent of rupture was not associated with a geometric feature of the faulting. This is observed behavior, and we recognize that rupture can be constrained in other ways (*2, 8*), particularly in vertical extent (*9, 10*).

The best studied earthquake that is limited in extent by geometric features occurred in California on 28 June 1966 with a surface-wave magnitude (M_s) of 6.5. Rupture was reported to have propagated to the southeast from an epicenter near Parkfield (*3*). The epicenter was associated with a 5° bend in the fault, and apparently rupture stopped after propagation past a bend and offset in the faulting near U.S. Route 446 (Fig. 1a). Earlier earthquakes with similar characteristics apparently occurred along the same fault segment in 1881, 1901, 1922, and 1934 (*7, 11*).

An earthquake of M_s 7.5 took place at Luhuo, China, on 6 February 1973. The epicenter was near a bend at the center of the mapped surface traces (*12*), and rupture extended to the southeast and northwest (Fig. 1b). Information about the regions of termination is not available.

The 6 September 1975 earthquake in Lice, Turkey, had M_s 6.7. The region of the fault that is reported to have moved (*13*) is approximately enclosed by the intensity VIII contour (Fig. 1c) (*14*). The International Seismological Centre (ISC) epicenter of 38.51°N, 40.77°E, falls near the bend at the eastern extent of the damage region but, because of errors of location in the region (*15, 16*), cannot be regarded as very reliable. However, Nábělek (*17*) has shown that rupture propagated from east to west, and thus to be consistent with the surface rupture and damage distribution we conclude that the ISC epicenter is approximately correct. Rupture started near a bend in the faulting 20 km east of Lice and terminated near a bend 5 km to the west (Fig. 1c).

The earthquake at Tangshan, China, on 27 July 1976 was of magnitude M_s 7.8. Reported surface faulting was sparse and ambiguous, so in Fig. 1d we show only the trends of the largest aftershocks and the location of the main shock (*18*). The epicenter of the main shock occurred near the center and at a bend in the aftershock distribution, and rupture propagated to the southwest and then,

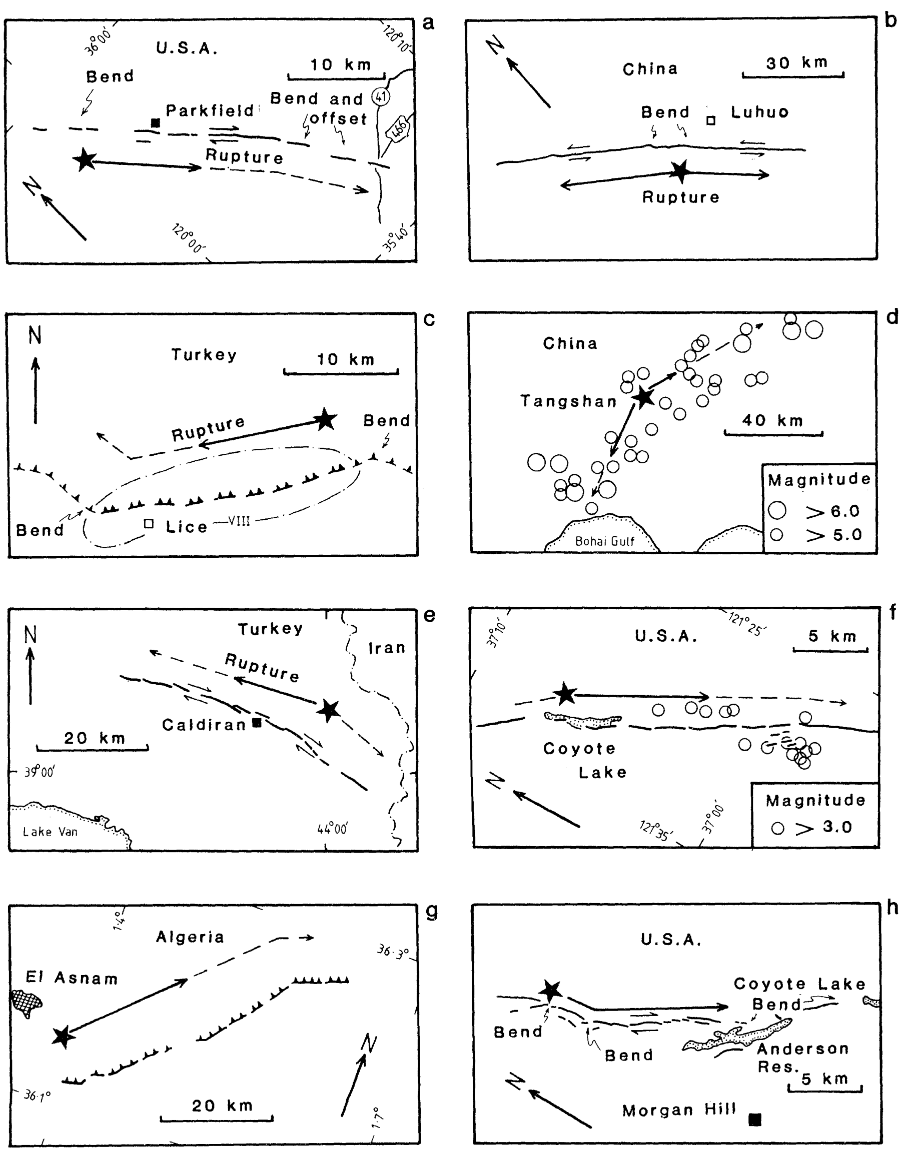

Fig. 1. Relation of bends in faulting to the initiation and termination of earthquake rupture for eight events: (a) Parkfield, California; (b) Luhuo, China; (c) Lice, Turkey; (d) Tangshan, China; (e) Caldiran, Turkey; (f) Coyote Lake, California; (g) El Asnam, Algeria; and (h) Morgan Hill, California.

after a few seconds, to the northeast (*19*). At the southern end the rupture terminated by thrust faulting. The largest aftershock (M_s 7.1) occurred at the northern end and had a normal faulting mechanism.

An earthquake occurred at Caldiran, Turkey, on 24 November 1976 (M_s 7.4). The surface break was well exposed (*20, 21*). It formed two limbs of approximately equal length striking 40° with respect to each other (Fig. 1e). The largest surface displacements were mapped on the western limb. The ISC epicenter of 39.05°N, 44.04°E, falls approximately at the junction of the two limbs. It has been shown from surface-wave (*22*) and body-wave (*23*) studies that the primary energy release was from the rupture on the western limb, which propagated westward from the epicenter near Caldiran. The rupture on the eastern limb followed within a few seconds (*23*). Information about rupture termination is not available.

The 6 August 1979 earthquake at Coyote Lake, California (M_s 5.7), (Fig. 1f) had a well-located epicenter near Coyote Lake and near a bend in the Calaveras fault. The surface ruptures for the event were small (although the Calaveras fault is a clear morphological feature in this region), and so the extent of rupture is indicated on the basis of the larger aftershocks (*24*). The rupture apparently terminated near a change in the fault strike in the south.

The 1980 earthquake in El Asnam, Algeria, has been studied extensively. The rupture initiated at the southwest end of a thrust fault (*5, 25–27*). The faulting in this region is geologically new whereas that to the northeast is well advanced, and the earthquake reactivated well-established faults. King and Yielding (*5*) have suggested that the onset of rupture was associated with the creation of new faulting in the southwest, and thus, unlike the other events discussed here, it did not start near a bend in preexisting faulting but rather in a complex net of new faulting with varying strikes. The rupture terminated in the northeast, where it reactivated faults of a different strike (Fig. 1g).

An earthquake (M_s 6.1) that caused substantial damage in Morgan Hill, California, occurred on 24 April 1984 on a segment of the Calaveras fault immediately north of the segment that ruptured in the 1979 Coyote Lake event. Surface ruptures have not been found, but aftershocks occurred in a zone beneath the surface geomorphic expression of the fault (Fig. 1h). The epicenter was close to a bend in the fault at the northern end of the aftershock zone (*28*). The rupture propagated to the south, and a late burst of energy was released in the region of Anderson Reservoir. Although the exact extent of rupture is not precisely defined, it apparently started at the more northerly of two bends, forming an offset in the fault, and propagated south to near the initiation region of the Coyote Lake earthquake (Fig. 1f).

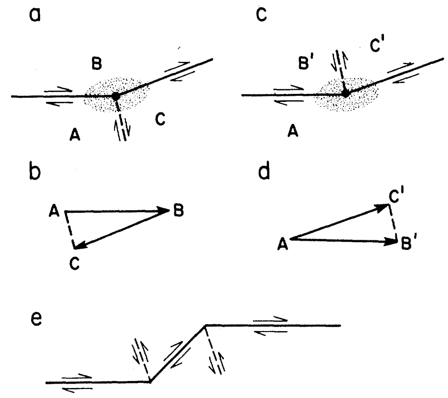

Fig. 2. Bends in faults require the creation of a third direction of faulting (but not necessarily a third major fault). Two possibilities are shown: bends (a and c) with the corresponding vector triangles (b and d). The zone around the projected intersection point (shown by hatching) must deform. A fault offset (e) can be considered a pair of bends or several sets of bends of opposite signs.

Contemporary hypotheses on the initiation and termination of earthquakes are based on the concepts of "asperities" and "barriers." The former idea, although modified by other investigators (*29*), owes its origin to explanations of frictional behavior on a microscopic scale (*30*) and carries the idea of unfractured interlocking topography on the two surfaces of a fault. These surfaces must be broken by new fractures to permit motion. The concept originally carried with it the idea of previously separated surfaces being brought into incomplete contact, an inappropriate concept for the in situ creation of fracture.

The barrier concept has a different origin. Madariaga (*31*) and others (*1, 2*) have noted that at high frequencies faults radiate seismic energy mainly when rupture fronts accelerate or decelerate. Thus the origin of radiation must be traceable to features that require the rupture front to behave in this fashion.

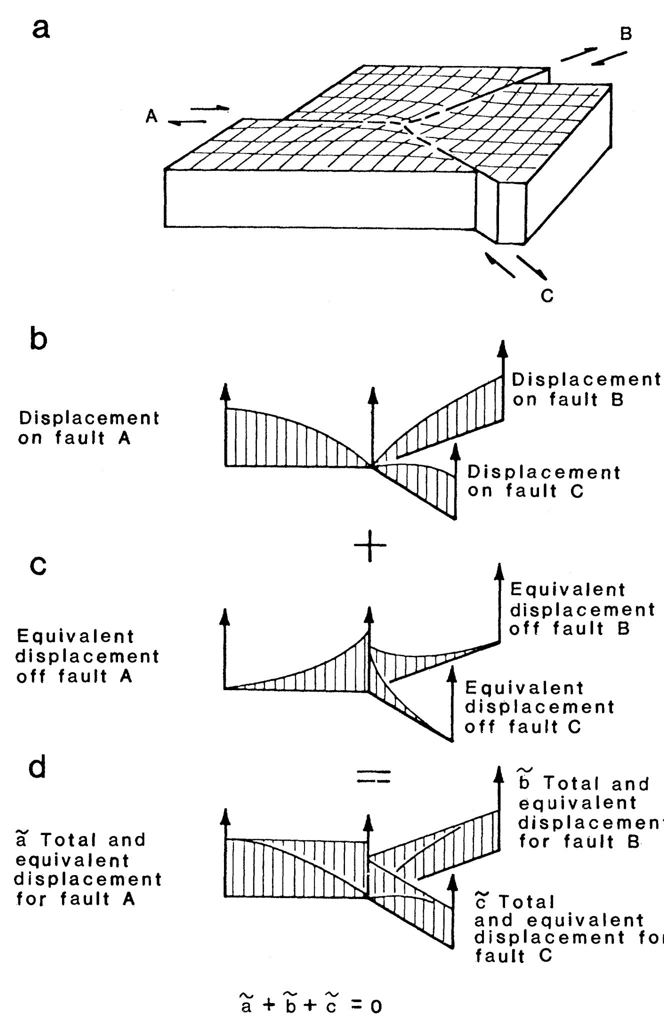

Fig. 3. Deformation near a three-fault junction. (a) The geometry of deformation. (b) Plausible main fault slip distributions. (c) The deformation that must be accommodated by secondary faulting. For continued deformation the slip in (b) and the equivalent slip in (c) must sum to give apparently constant slip (d).

The original use of the term "barrier" to explain such behavior was only loosely constrained by any preconceptions about the mechanical processes occurring on the fault (*32*). The idea, however, has subsequently been extended to incorporate possible changes of fault strength (strength barriers) and fault geometries (geometric barriers) (*2*). The former apparently do not control the lateral extent of rupture in our examples and are not considered further here.

King and Yielding (*5*) extended the ideas of geometric barriers associated with a change in orientation of two active faults and divided them into two categories, conservative and nonconservative. In the former the slip vector is the same for both faults (it is therefore parallel to the line of intersection of the two fault planes), and in the latter the slip vector differs on the two planes (as in the examples given here). The use of the terms "conservative" and "nonconservative" derives from a similar use in the theory of crystal dislocations (*33*). The problem of nonconservative barriers has been investigated by King (*6*), who showed that the intersection of two faults on which finite motion occurs requires an appearance of a third direction of faulting (Fig. 2). However, since displacement on the three strike-slip faults must come to zero at the intersection, other deformation must occur to permit fault motion (Fig. 3). Figure 4 shows the implications of accommodating this motion by further faulting. It is impossible to introduce small faults without reproducing the fault intersection problem at a smaller scale. Thus motion on the main faults will produce subsidiary faulting in a zone around the junction at all scale sizes. These faults need not actually be of the form shown schematically in Fig. 4, although the figure does illustrate the need for multiscale faulting. Geometric forms that the faults can adopt have been discussed by King, who has suggested certain rules that govern their configuration, rules that also provide an explanation for the power law distribution of earthquake magnitudes (*6*).

Figure 5 shows the role that bend geometry plays in the earthquake cycle. In Fig. 5A motion on main fault **a** propagates toward the junction and causes faults **b** and **c** to move. These motions in turn cause the surrounding system of faults to move. The first result is that the deformation is spread over a broad zone (process zone), which absorbs a large part of the stress at the tip of main fault **a** and reduces the stress transferred to faults **b** and **c**. The second result is that motion on faults in different directions causes fault planes to lock. These offsets form asperities that must be broken before the continuity of the old fault surfaces can be reestablished. Their creation prevents extension of motion on the main faults much beyond the junction. Faulting must extend past the point of intersection of the main faulting before a process zone is created and locking can occur. It is only when this happens that the earthquake rupture can terminate.

The density of faulting and consequently the density of asperities created by the termination process are greatest near the junction (Fig. 5B). This is evident intuitively because the bend zone must deform most as a result of finite motion. Before a large event ruptures the entire fault plane **b** as a result of increasing tectonic load, earthquakes will tend to occur near the boundary of the process zone created by the earlier event [Mogi's doughnut (*34*); Fig. 5C]. In the immediate region of the hypocenter of the future large event, the fragmentation produced by the earlier event restricts activity to very small magnitudes (Fig. 5D). Suitable small events progressively break asperities on the main fault plane **b** and in due course initiate the next main event (Fig. 5E).

We show in Fig. 5 only one fault bend, whereas in a real fault system there are many bends that interact with one another. Therefore, we do not suggest (in obvious violation of observations) that one earthquake always initiates where

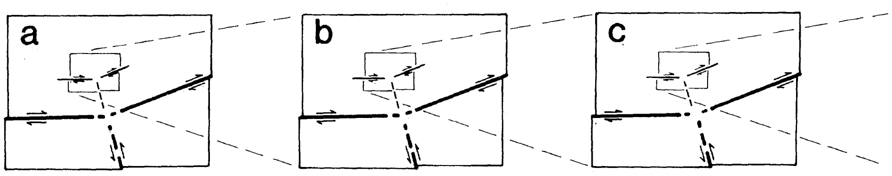

Fig. 4. Deformation at a three-fault junction can be accommodated by smaller secondary faults subparallel to the main faults (a). These meet at an angle creating yet smaller faults (b and c). Thus fracturing occurs at all scales. Constraints on realistic fault geometries are possible (*6*).

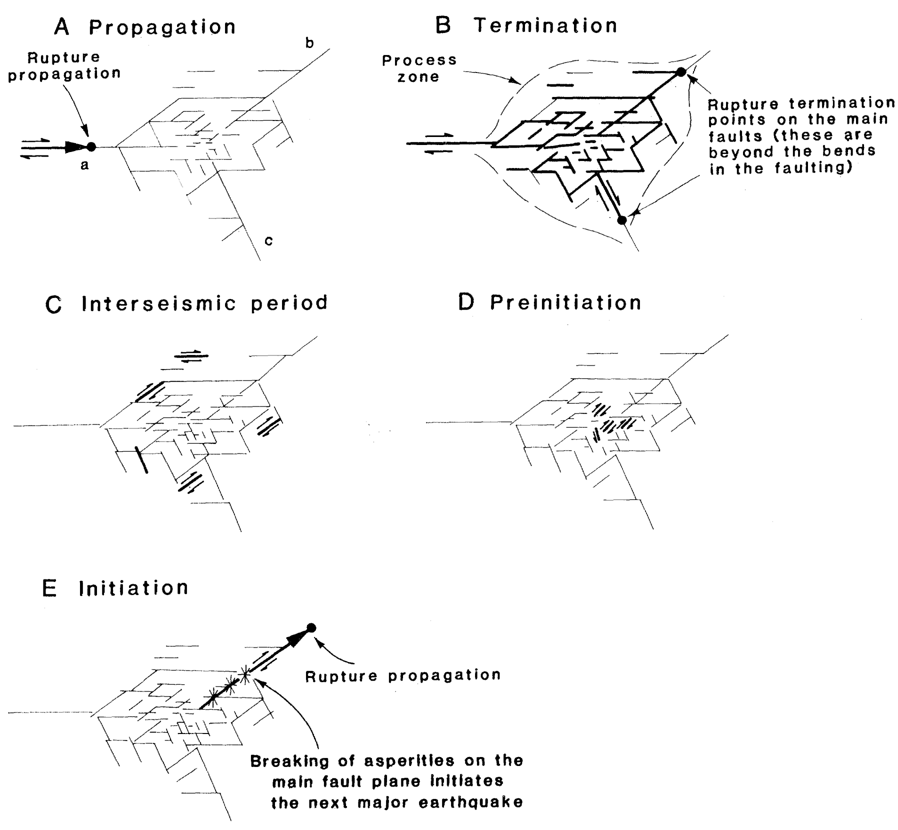

Fig. 5. Role of the bend region in the earthquake cycle. (A) Propagation of the main event toward the bend. (B) The termination process. Many faults move in the region of the bend, both in the last phases of the main shock and as aftershocks. (C) Interseismic processes. (D) Preinitiation processes. Because of fragmentation of the main fault surfaces, larger events (foreshocks) can only occur at a distance from the junction of the main faults. (E) Earthquake initiation associated with the final breaking of asperities, which reestablishes the continuity of the fault plane on which the next major event occurs (*29*).

the previous one terminates, but simply illustrate the way in which the termination process of one event sets up the initiation environment for some future event.

The foregoing examples and the model suggest that bend zones are critical in earthquake mechanics and initiation and should be carefully monitored for precursory effects. The model suggests that, because bend zones by their nature involve faulting on a wide range of scales, earthquakes should also be monitored over a wide scale range if the physical processes in these regions are to be understood. Possibly, downhole seismometers should be used to detect tiny asperity-breaking events in the hypocentral region. The monitoring should not be too localized since activity prior to a main event can occur at a distance from the epicenter, forming a Mogi doughnut (*34*) (Fig. 5C).

It is evident that bends in faults are, in the long term, unstable features, and new fault geometries must inevitably result from continued tectonic motion. Nonetheless, repeated motion on fault segments does occur and produces clear morphological features from which the expected lifetime of a given segmentation geometry may be judged. One of the problems we face in characterizing the bend regions is also a geomorphological one. Although multiscale faulting may be expected to occur at depth, the faults will in general be too small to create surface breaks. We cannot expect the surface fault geometry to represent that at depth except for the grossest features. Individual small events do not generally form surface breaks, but repeated motion often results in the formation of near-surface warping, folding, and secondary faulting (*5, 9, 35, 36*). Identification of active horizontal drag-folds in the case of strike-slip faults and active anticlines or monoclines in the case of dip-slip faults is therefore important. It is also important to distinguish between secondary faulting that is a consequence of near-surface folding processes driven by fault motion at depth and surface faults that are the direct surface expression of seismic faulting at depth.

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A Model for a Seismic Computerized Alert Network

Abstract. *In large earthquakes, damaging ground motions may occur at large epicentral distances. Because of the relatively slow speed of seismic waves, it is possible to construct a system to provide short-term warning (as much as several tens of seconds) of imminent strong ground motions from major earthquakes. Automated safety responses could be triggered by users after receiving estimates of the arrival time and strength of shaking expected at an individual site. Although warning times are likely to be short for areas greatly damaged by relatively numerous earthquakes of moderate size, large areas that experience very strong shaking during great earthquakes would receive longer warning times.*

The purpose of a seismic computerized alert network (SCAN) is to provide short-term warning (as much as several tens of seconds) of imminent strong ground motion from large earthquakes. In earthquakes of great fault length, substantial damage often occurs at great distances from the earthquake's epicenter. It is possible to construct a system that would quickly detect strong ground motions in the epicentral area of major earthquakes. Information about the nature of an ongoing earthquake could then be transmitted to areas that may be strongly shaken when seismic energy propagates to them. This information could be processed automatically by individual users, and appropriate safeguard actions could be initiated.

The great earthquake of 1857 that ruptured a 300-km segment of the San Andreas fault in southern California is an example of how a SCAN could provide more than a minute of warning time before the occurrence of strong shaking in a heavily populated area. There is evidence that the rupture initiated in the vicinity of Parkfield (*1*), a small town 275 km northwest of metropolitan Los Angeles. It seems likely that rupture propagated south toward the Los Angeles region at a velocity of about 3 km/sec or less, and the strongest shaking in the Los Angeles region probably occurred at least 100 seconds after the ground began to shake at Parkfield.

In similar earthquakes, a SCAN could provide users with information during this time so that they could initiate certain safety precautions. The most suitable applications are in those operations that come under computer control and can be safeguarded quickly. For example, a SCAN could initiate (i) electrical isolation and protection of delicate computer systems, (ii) isolation of electric power grids to avoid widespread blackouts, (iii) protection of hazardous chemi-