IMPLICATIONS OF SURFICIAL STRIKE-SLIP FAULT PATTERNS FOR SIMPLIFICATION AND WIDENING WITH DEPTH

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Confirmation of this general relation is provided by the relatively deeply eroded exposures of fault zones in the San Andreas system, which show typically very wide belts of crushed rock or gouge. These characteristics derive in part from the large number of faulting events and the great amount of total strain that relatively old rocks in the fault

Kinds of complex fault patterns

Geometric complexity of faulting at the surface arises both from branching of continuous breaks and from en echelon discontinuities. Branching of surficially simple and continuous faults is a special case where generally downward simplification, perhaps into a single slip 'surface at depth, is not implied. Beyond the point of branching, with appropriate geometry at the surface, that the two faults maintain their separate identity at depth generally can be expected. This case will not be discussed further here, since each branch may separately be consider+ as a single fault or fault zone. En echelon patterns of faults create apparent complexity of more diverse kinds. Such patterns can'be categorized according to their size, the sense of stepover relative to the. sense of horizontal slip, and also according to whether beyond the limits of the en echelon overlap the single emerging strands are approximately aligned or are significantly misaligned. Table 1 summarizes these categories and examples of 'them.

Table 1. Categories of en echelon faults.

1. Small scale, opposite stepover sense, out of line.
2. Large scale, opposite stepover sense, out of line.
3. Small scale, same stepover sense, out of line.
4. Large scale, same stepover sense, out of line.
5. Small scale, opposite stepover sense, in line.
6. Large scale, opposite stepover sense, in line.
7. Small scale, same stepover sense, in line.
a. Large scale, same stepover sense, in line.

Examples:

1. Very common at many places on San Andreas (see Wallace, 1973). Commonly observed at very small scale (fraction to few meters) in earthquake surface rupture patterns.
2. Fairly uncommon. Coyote Creek fault San Jacinto zone at Ocotillo Badlands, Calif.
3. Very common in San Andreas system--common situation for sag ponds.
4. Common in some parts of San Andreas system--Gulf of California situation for large grabens San Jacinto Valley.
5. Common. Dead Sea rift, 12-16 km wide (Quennell, 1956). 1940 Imperial Valley surface rupture at border.
6. No examples known.
7. Uncommon. 1940 Imperial Valley surface rupture.
a. No examples known.

To place these variables in perspective, further explanation should be made to rationalize their significance to the problem. Small-scale examples of en echelon faulting, recorded either geologically, geomorphically, or as cases of historic surface rupture, here are taken as models of what possibly happens at greater dimensions, including those comparable to focal depths. That a continuous gradation in size of these fault patterns has been observed for strike-slip faults suggests that their comparison is justified, at least as a qualitative approximation. Small en echelon features produced during earthquakes are especially revealing of fault geometry with depth if they are incipient (displacement —— 0) or if the displacements are on the order of 1-2 meters. In examples of the latter, the extensional fissures are opened sufficiently so that the character of the vertical changes in the geometry may be visible from the ground surface, or they can be physically entered. With larger surface displacement (≥ 3 m) in a single event, these geometric features of en echelon strike-slip rupture are mostly destroyed, at least in alluvial or other young surficial deposits. Natural and artificial exposure of faults also provide data on the depthwise geometry of the structures. If the distance between such observations is small, the geometric interrelations of the faults can be worked out with considerable accuracy. Trenching of faults in alluvial materials is particularly useful in working out the geometry of fault surfaces.

Sense of stepover is important because it defines whether the body of material lying between the en echelon faults is in a compressional or extensional regime. By sense of stepover being the same or opposite, I mean that left-lateral faults step over to the left, and so on through the four possibilities for both right- and left-slip faults.

Alignment of the fault at opposing ends of an en echelon overlap zone is passive but suggestive evidence that at depth the fault might be continuously nearly linear. The scale of the overlap then is approximately related to the depth at which the double break converges into a single one.

Origin of surficially complex patterns

Fault movements are generated by sudden displacements at depth and propagate toward the surface. In previously broken rock, anisotropies due to preexisting fracture surfaces tend to guide new events of movement more or less along the same surfaces up to very near the surface. In an area of active alluvial accumulation, new and previously unbroken sediment may cap the older fractures, or alternatively, possible readjustment of detrital grains in the near surface by meteoric processes may have virtually rehealed earlier fractures. In either of these cases, much of the complexity of a typical strike-slip surface rupture originates within a mantle of either previously unbroken or rehealed sediment. A typical fault trace in alluvial material is shown in Figure 1. The Motagua fault rupture of 1976 in Guatemala, as an example, generally resembled the pattern on the left side of Figure 1 throughout its 230 km length with only isolated examples of the pattern on the right where recent alluvial material had accumulated to unusually great thickness.

Some very unusual exposures of the 1976 Guatemalan fault rupture near Manzanotes revealed open en echelon cracks that converged downward to a single smooth and closed slip surface within 1–2 meters of the ground surface. In these examples it could be easily seen because of the nearly 1 m of displacement that the individual, extensional en echelon cracks were opened helical fractures with right-hand twist. Figure 2 shows a block diagram with the outline of an open surface crack shaded and with a series of cross sections to show how the crack closes downward and how the fracture dips toward the underlying vertical and closed fault surface. A succession of extensional cracks on both ends of this example all showed that the smooth slip surface at approximately 1 meter depth was shared by all of the open cracks. Thus, in spite of the surface complexity, the fault surface was single, smooth, and very nearly a vertical plane within 1 meter of the ground surface. What produced such spectacular helical curvature in the extensional crack was the thinness of a residual soil which, although previously broken, had become rehomogenized by

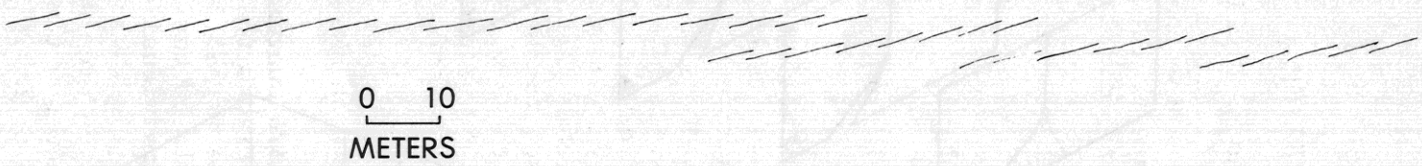
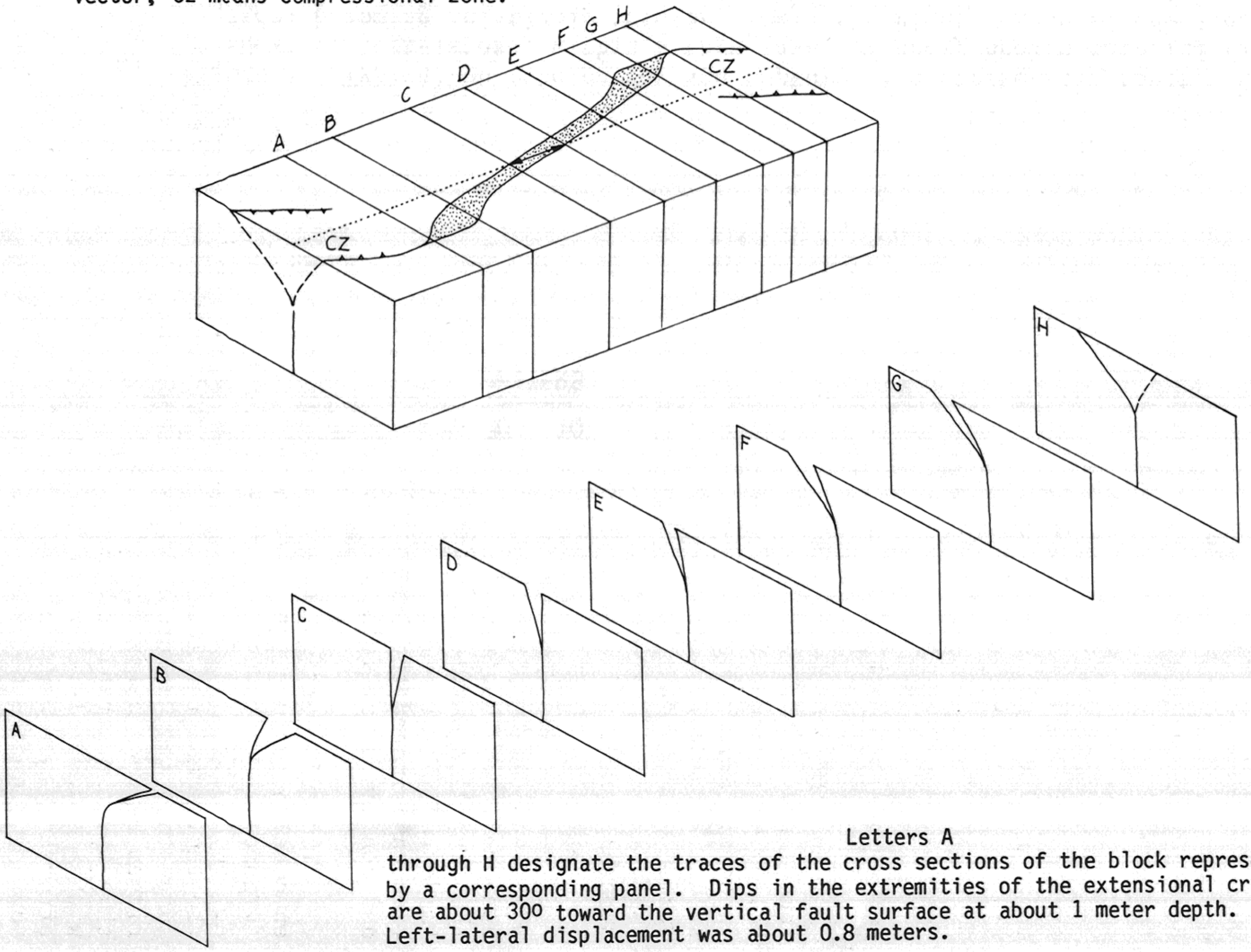


Figure 1. Typical en echelon surface rupture of a strike-slip fault. Example shown is left-lateral within a thin layer of newly broken material (left side) becoming relatively thicker toward the right. Each of the line segments represents a crack, in the direction of which there is a lateral component of slip and perpendicular to it an extensional component of slip. In the region of overlap of the separate cracks are compressional zones that exhibit a wide assortment of compressional features. This is a typical "mole track" consisting of a series of alternating compressional and extensional zones.

Figure 2. Block diagram and cross sections of an extensional crack on the Motagua fault near Manzanotes, Guatemala. In the block view the open crack is represented by the shaded area, within which the arrow represents the slip vector; CZ means compressional zone.



Letters A through H designate the traces of the cross sections of the block represented by a corresponding panel. Dips in the extremities of the extensional crack are about 30° toward the vertical fault surface at about 1 meter depth. Left-lateral displacement was about 0.8 meters.

weathering processes. The material behaved as though it was previously unbroken.

The Guatemalan example discussed above is probably not a deviation from the general rule for ground ruptures or "mole tracks" of strike-slip faults but rather an extreme example of the downward geometric simplification compressed to a very small dimension. A similar downward simplification to a smooth fault surface at a depth of 1 meter was noted in Japan during the Izu-Hanto-Oki earthquake of 1974 (Matsuda and Yamashina, 1974). We can surmise, but generally not prove by direct observations made to date, that perhaps most en echelon extensional cracks in a strike-slip zone are helices whose pitches are variable, and in the general case, a fault in deep alluvium may not exhibit obvious curvature at all, even though the displacement might be large enough to permit viewing the interior of the fracture directly from the ground surface.

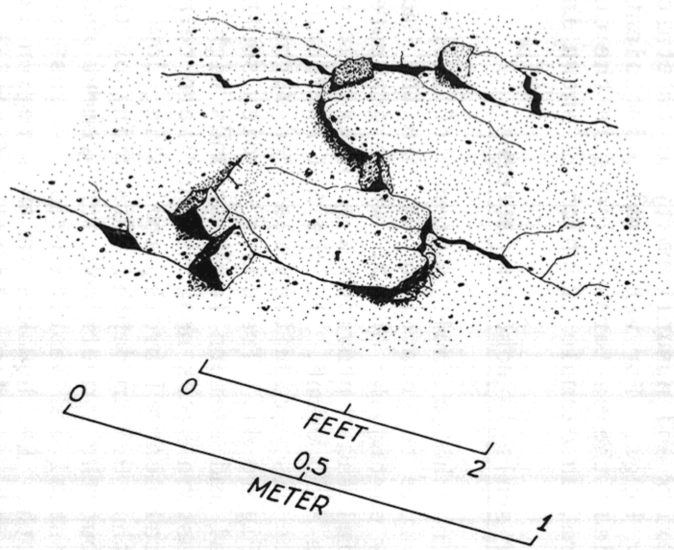
The compressional features that terminate the extensional cracks in the strike-slip event have not been illustrated in Figure 2 because of their complexity and nonuniformity of fracture pattern when displacement is relatively large. For very small, incipient strike-slip movements in alluvial materials the patterns evident in the compressional zones appear to be more uniform, an example of which is shown in Figure 3.

Larger scale en-echelon patterns

En echelon fault patterns of large dimension imply complexity of a fault zone to greater depth than the "mole track" examples. The Imperial Valley earthquake of 1940 which generated surface displacement on the Imperial fault provides a good example of an en echelon fault pattern for a strike-slip event. At the All American Canal the dimension of the zone of surface discontinuities measured across the trend of the fault is about 75 m (see Figure 4). Trenching studies south of the canal suggest that the central and eastern fault strands might converge at relatively shallow depth. The eastern break near its northern terminus dips at 76 degrees toward the vertical central break, indicating downward convergence within only slightly more than 0.1 km depth. Trenching of the western fault strand has not been done but the symmetrical arrangement and somewhat greater distance between the central and western break suggest that convergence may occur within 0.2 km depth. Earthquakes in this region lie far below such surficial complexities, and indeed the Imperial fault at this location probably is very smooth and continuous at focal depths.

The 1968 Borrego Mountain earthquake produced surface ruptures on two en echelon rupture zones separated by 2 km, the width of Octillo Badlands (Figure 5). Although the dips of the faults marginal to the badlands have not been observed either in natural or artificial exposures, the geometry of the faults and the intense folding of Quaternary sediments in the badlands suggests strong compression in a sense that is analogous to the compressional ridges between extensional cracks on a "mole track." It is quite possible that the two strands of the Coyote Creek fault converge to one zone, probably within a few kilometers of the surface, as shown in Figure 6. Epicenters of aftershocks of the 1968 event tend to confirm the presence of a single shear surface beneath the badlands (Hamilton, 1972, Fig. 13). That the two should converge into a single fault resembling the surficial shears probably is not

Figure 3. Incipient "S" shaped double thrust formed in compressional zone between en echelon fractures of the Coyote Creek fault associated with the Borrego Mountain earthquake of 1968. Location of this example is southeast of Ocotillo Badlands where right-lateral displacement was on the order of 5 cm. With large lateral displacement the double thrust features are progressively destroyed.



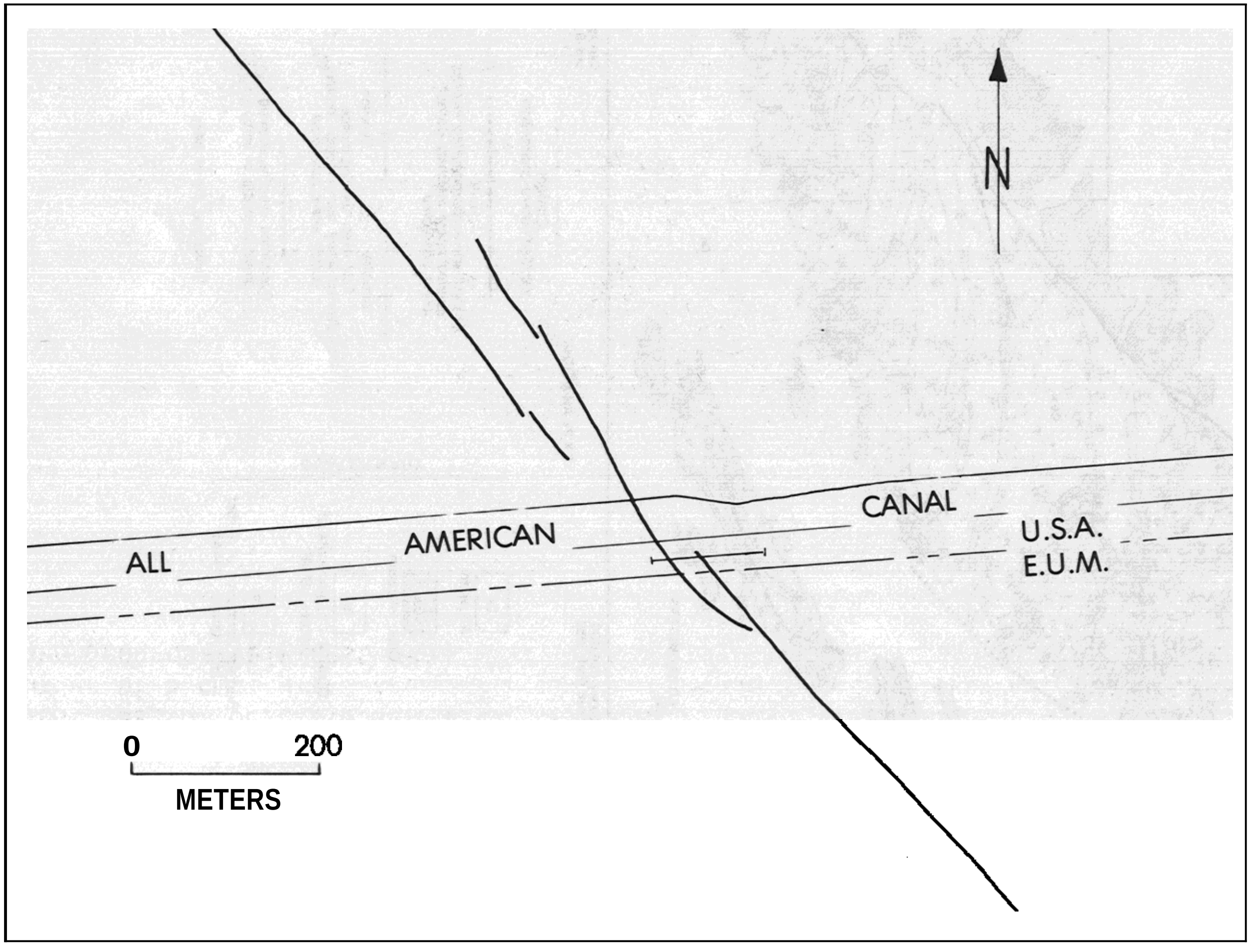
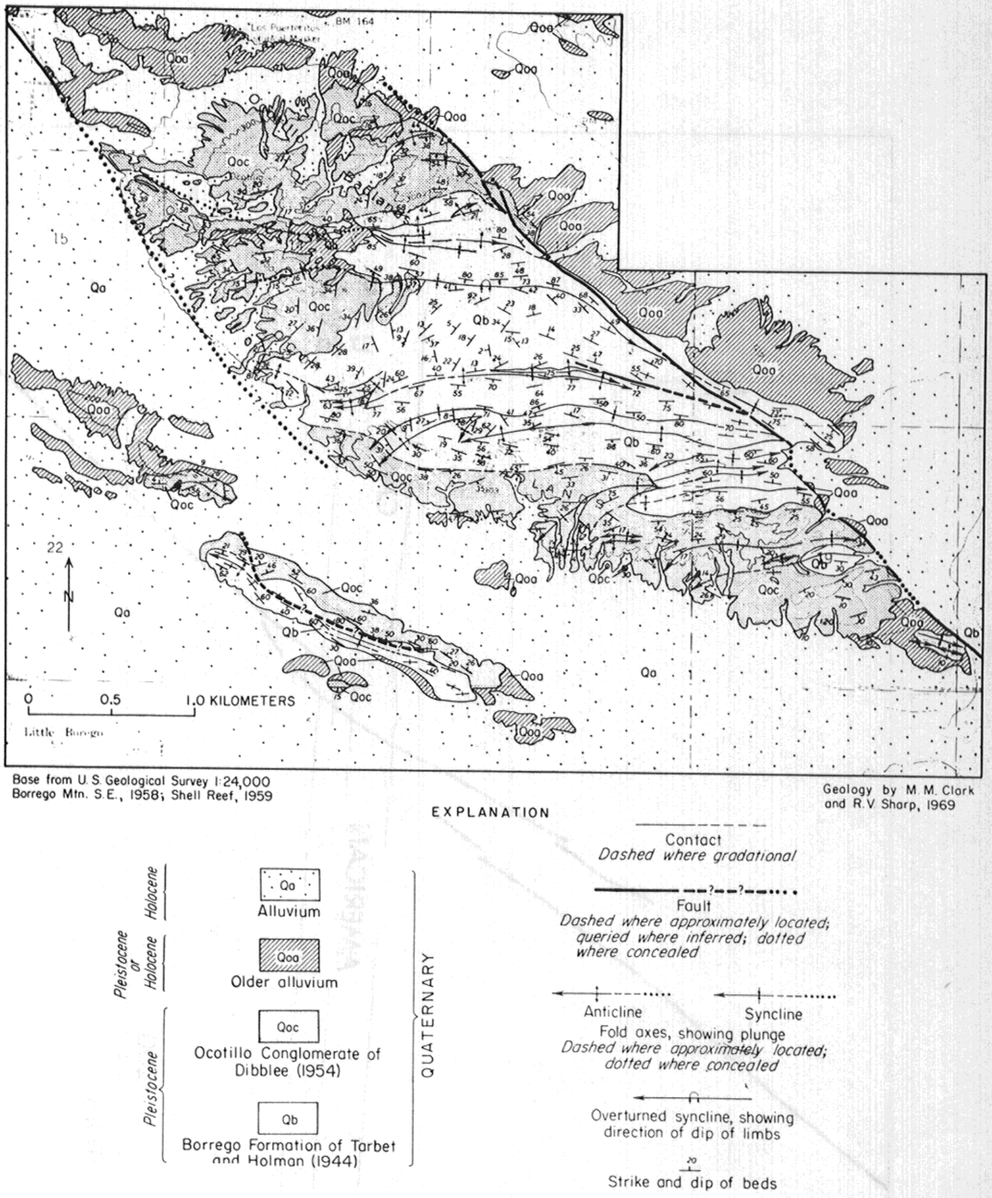


Figure **4.** En echelon breaks in the Imperial fault movement of **1940.** Heavy line between All American Canal and international boundary shows position of trench.



Base from U.S. Geological Survey 1:24,000
Borrego Mtn. S.E., 1958; Shell Reef, 1959

Geology by M. M. Clark
and R. V. Sharp, 1969

Figure 5. Two strands of the Coyote Creek fault bounding compressed Quaternary sediments in Octillo Badlands. Geologic map from Sharp and Clark (1972).

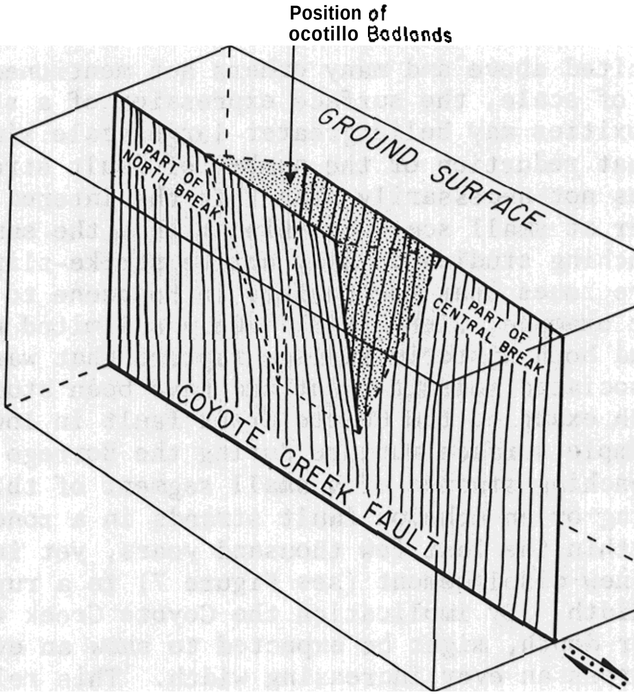


Figure 6. Three-dimensional view of possible configuration for Coyote Creek fault beneath Octillo Badlands. Distal ends of volume of strongly compressed sediments (stippled) shown by dashed and dotted lines. Reproduced from Sharp and Clark, 1972, Figure 94.

a reasonable expectation. The convergence may well be a zone of extreme complexity as well as much wider than the surficial exposures of the faults.

The Dead Sea rift could be a potential example of major en echelon faults that have produced a zone of crustal extension whose 12-16 km width is comparable to crustal thickness. Quennell (1959) has argued such an origin, and, although Picard (1966) questions the latter's tectonic mode of origin of the rift, he shows that faults on opposite sides of the sea dip toward one another at steep angles. The possibility remains that the Dead Sea rift is a large-scale example of downward convergence of separate shears making up a complex zone of faulting at the surface.

Discussion

The examples cited above and many others not mentioned suggest that over a broad range of scale, the surface expression of a strike-slip fault with all its complexities may belie greater large-scale simplicity at depth. I emphasize here that reduction of the number of fault strands in a downward converging zone does not necessarily mean that the internal structure in the zone becomes simpler at small scale or thinner than the sum of the multiple shears above. Trenching studies on many active strike-slip faults suggest very complex rupture zones near the surface in Holocene to Pleistocene materials (see, for example, Sieh, 1978). Only a limited number of strike-slip faults have had both historic surface rupture that was carefully documented after an associated seismic event and have been studied in detail by trenching. One such example, the Coyote Creek fault in lower Borrego Valley had a relatively simple surface rupture during the Borrego Mountain earthquake of 1968. Trenching studies of a small segment of this fault show that at least 18 branching or en echelon fault strands in a zone about 30 m wide have been active within the last few thousand years, yet in 1968, only two of these exhibited new displacement (see Figure 7) in a rupture zone only about 6 meters in width. By implication the Coyote Creek fault, if it were excavated to greater depth, might be expected to show an even greater number of fault strands across an ever increasing width. This relation with depth and the possibility of increased total strain with depth contributing to the formation of gouge materials of greater width downward suggests a simple picture of downward increasing width of the fault where large en echelon patterns do not exist.

A different relation of historic surface rupture to earlier events of slip has been found by trenching the Imperial fault near the U.S.-Mexican border. Trenches at that location showed that strata of approximately 1000 years ago have been broken only by fault strands that moved in 1940, with no suggestion of downward increase in the number of fault strands. Although we can conclude that there must be great variability in the way individual faults may behave in the near surface at specific locations and times, we are left with the well-documented fact that strike-slip fault zones, where exposed in old terrains, are much wider and more complex than the same fault zones in young materials.

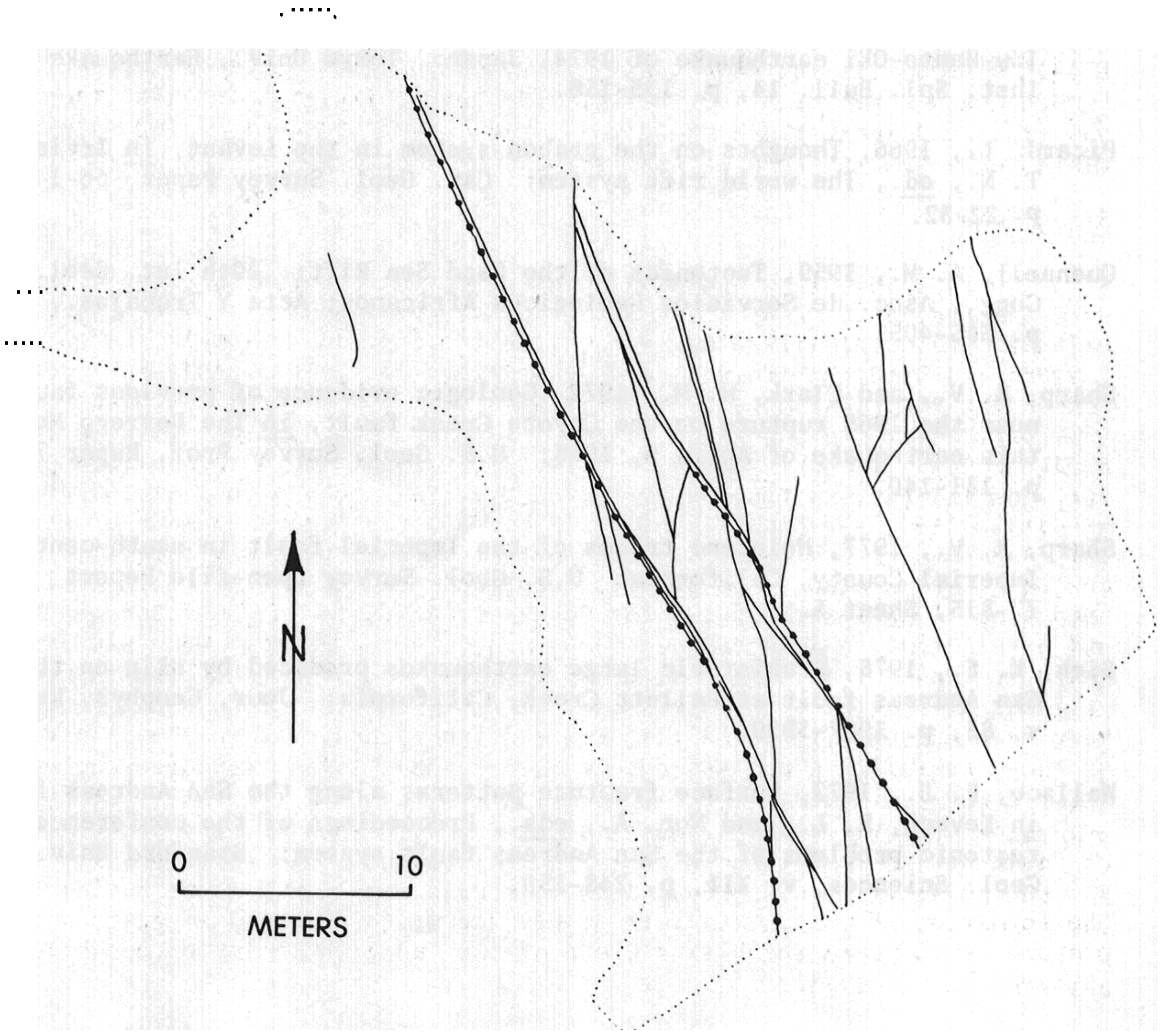


Figure 7. Fault strands of the Coyote Creek fault at a location in Lower Borrego Valley. The faults shown by simple lines have been active within the last 5000 years. The lines with circles are the two strands that were reactivated in 1968. The dotted line represents the boundary of trenching data on the existence of faults.

References

Hamilton, R. M., 1972, Aftershocks of the Borrego Mountain earthquake from April 12 to June 12, 1968, in The Borrego Mountain earthquake of April 9, 1968: U.S. Geol. Survey Prof. Paper 787, p. 31-54.

Matsuda, T., and Yamashina, K., 1974, Surface faults associated with the Izu-Hanto-Oki earthquake of 1974, Japan: Tokyo Univ., Earthquake Res. Inst. Spl. Bull. 14, p. 135-158.

Picard, L., 1966, Thoughts on the graben system in the Levant, in Irvine, T. N., ed., The world rift system: Can. Geol. Survey Paper 66-14, p. 22-32.

Quennell, A. M., 1959, Tectonics of the Dead Sea Rift: 20th Int. Geol. Cong., Asoc. de Servicios Geologices Africanos; Acta Y Trabajos., p. 305-405.

Sharp, R. V., and Clark, M. M., 1972, Geologic evidence of previous faulting near the 1968 rupture on the Coyote Creek fault, in The Borrego Mountain earthquake of April 9, 1968: U.S. Geol. Survey Prof. Paper 787, p. 131-140.

Sharp, R. V., 1977, Holocene traces of the Imperial fault in south-central Imperial County, California: U.S. Geol. Survey Open-file Report 77-815, Sheet 5.

Sieh, K. E., 1978, Prehistoric large earthquakes produced by slip on the San Andreas fault at Pallett Creek, California: Jour. Geophys. Res., v. 83, p. 3907-3939.

Wallace, R. E., 1973, Surface fracture patterns along the San Andreas fault, in Kovach, R. L., and Nur, A., eds., Proceedings of the conference on tectonic problems of the San Andreas fault system: Stanford Univ. Pub. Geol. Sciences, v. XII, p. 248-250.