Historic Surface Faulting—Map Patterns, Relation to Subsurface Faulting, and Relation to Preexisting Faults

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Introduction

Examination of historic faulting events that have occurred in various parts of the world gives some insight into the angular relations, continuity, and widths (in map projection) involved in the process of faulting. It also permits some comparisons to be made between surface and subsurface effects, and between the surface faulting and preexisting faults. The main purpose of this paper is to summarize scattered data on faulting for use of geologists, engineers, and geophysicists who must solve practical problems related to faulting, and as background for those engaged in theoretical or experimental work on faulting.

In the first section of the paper, on map patterns, several events are described and generalized maps included. Some of the described examples also contain information pertinent to the following two sections of the paper, where information on other events is introduced in brief form. The final section summarizes those points that, to the writer, seem most important.

Map Patterns In Historic Surface Faulting

In this section a group of examples is described, some representative of several fault events and others which represent extremes in some particular aspect of faulting. The points of special interest in each of the events described in detail are listed in table 1. Only the larger aspects of fault patterns are considered--those measured in kilometers--but most of the patterns (en echelon, parallel, branching, and conjugate) also occur at much smaller scales.

Table 1.

Aspects of particular interest in the events described in this section of report.

Year	Country	Name of Earthquake	Fault Type*	Remarks
1891	Japan	Nobi	ss	Large en echelon stepovers; selective use of preexisting faults
1927	Japan	Tango	ss	Large en echelon stepovers; conjugate fault
1930	Japan	North Izu	ss	Two parallel traces; conjugate fault; appearance in tunnel
1943	Japan	Tottori	ss	Subsurface rupture apparently longer than geologic fault at surface
1944	Turkey	Gerede	ss	Largest stepover reported for any historic strike slip fault; parallel traces
1957	Mongolia	Gobi-Altai	ss or ros	Number of and displacements on subsidiary faults, and their distance from main fault; possible new faulting locally
1959	U.S.A.	Hebgen	n	Irregular rupture pattern; relation of surface faulting to focal mechanism solutions and aftershocks; possible new faulting locally
1968	Australia	Meckering	rv	Irregular rupture pattern; subsidiary faults on footwall as well as hanging wall; new faulting locally; discordance between surface faulting and focal mechanism solution
1970	Turkey	Gediz	n	Irregular rupture pattern; relation of surface faulting to focal mechanism solutions and aftershocks

*ss, strike slip; ros, reverse oblique slip; rv, reverse slip; n, normal slip

Nobi (Mino-Owari), Japan, 1891

This strike-slip faulting was recently restudied by Matsuda (1974) using all available historical data. The surface faulting (fig. 1) was about 80 km long and the maximum displacement was 8 m of left slip (Matsuda, 1974; Muramatu and others, 1964). The surface ruptures consist of several segments that are locally en echelon to the general trend; between the ends of these segments are gaps or "stepovers" of 1.9 km to 3 km, measured approximately at right angles to the traces. All of the surface faulting, including the secondary fault about 5 km north of Midori, occurred on preexisting faults that had Quaternary displacements (Matsuda, 1974, p. 116). Note that although the surface faulting was on preexisting faults, in several places it did not follow a particular fault to its end but instead shifted to a nearby fault.

Tango, Japan, 1927

The Tango Japan faulting of 1927 was associated with an earthquake of magnitude 7.6 (Geller and Kanamori, 1977). The principal surface rupture, called the Gomura fault, trended north- northwest and another rupture, the Yamada fault, trended northeast (fig. 2). The Gomura fault had a maximum left slip of about 3 m and in most places the west side was uplifted, the vertical displacement ranging up to about 1 m. A reverse component of slip on a steep fault is indicated by the trend of the fault trace as it crossed ridges and valleys (Yamasaki and Tada, 1928), by shortening detected by triangulation (Tsuboi, 1930), and by focal mechanism solutions (Wickens and Hodgson, 1967).

The Gomura fault consisted of at least 8 individual ruptures whose lengths ranged from 0.3 km to 3.5 km (Watanabe and Sato, 1928). The generalized map (fig. 2) shows that major stepovers between en echelon traces ranged from 0.4 km to at least 0.6 km.

The Yamada fault lay south of and nearly perpendicular to the Gomura fault. The Yamada fault was discontinuously exposed for 7.5 km but probably was longer as it intersected a bay at its northeast end. A right slip of 0.8 m and a vertical displacement of 0.7 m were observed by Yamasaki and Tada (1928). The orientation and displacement of the Yamada fault suggests that it has a conjugate relation to the Gomura fault.

Both the Gomura and Yamada faults followed preexisting fault scarps (Yamasaki and Tada, 1928). At one locality on the Gomura fault the surface rupture followed a N.12°W. clay-filled fissure 0.2 m wide in granite bedrock, but a north-south clay-filled fissure 2 m away showed no displacement (Watanabe and Sato, 1928, p. 9).

North Izu, Japan, November 26, 1930

This surface faulting, which was accompanied by a magnitude 7.1 earthquake (Gutenberg and Richter, 1954), was recently reviewed by Matsuda (1972) using all available published and unpublished historical data. The generally north-south rupture was about 24 km long, not including the minor ruptures near Ashino Ko Lake. Displacement was left slip, reaching a maximum of 3.5 m at one point, accompanied by 1.5 m of vertical displacement at the same locality. The side that was uplifted varied from place to place; focal mechanisms (Fara, 1964; Ichikawa, 1971) indicate left slip on a vertical fault; joining the surface fault with its position in a tunnel 160 m below the surface gives a dip of about 80°W. (Kuno, 1936a, fig. 1).

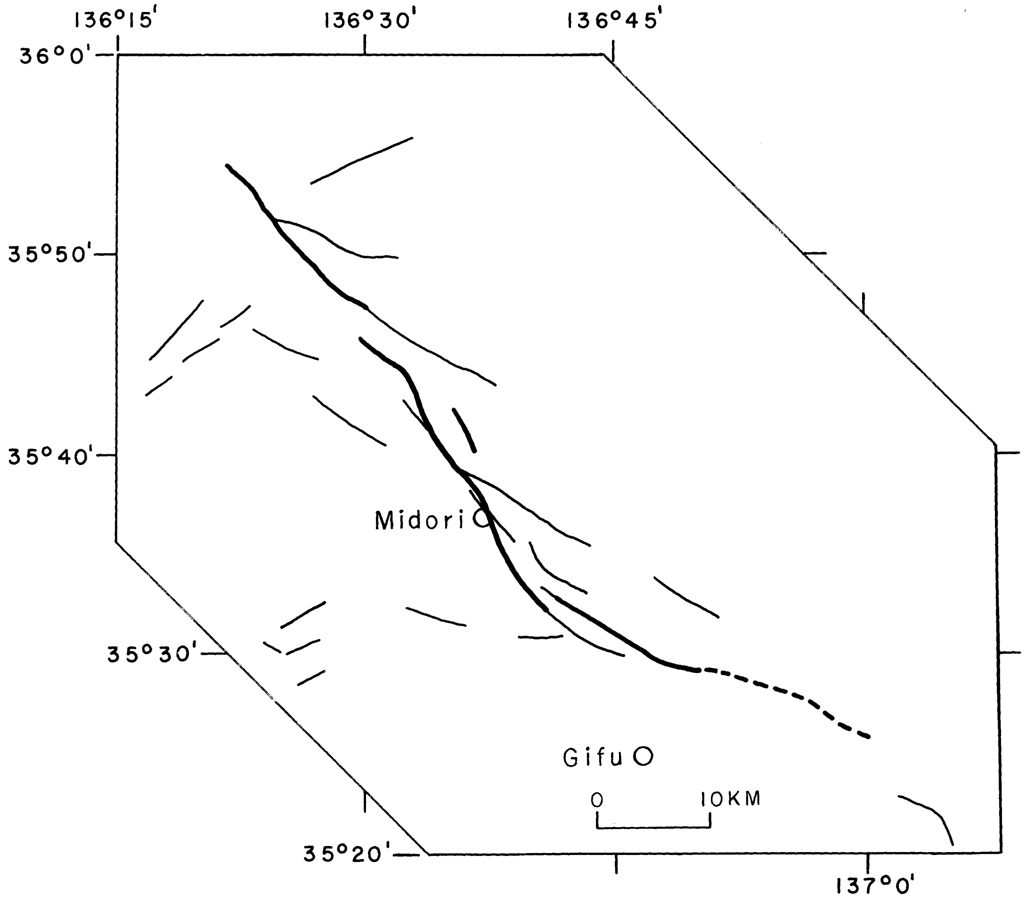

Figure 1. Map of Nobi, Japan, fault area. Strike slip surface faulting of 1891 is shown (generalized) by heavy line; other faults with Quaternary displacements shown by light lines. From Matsuda, 1974

JAPAN 1927

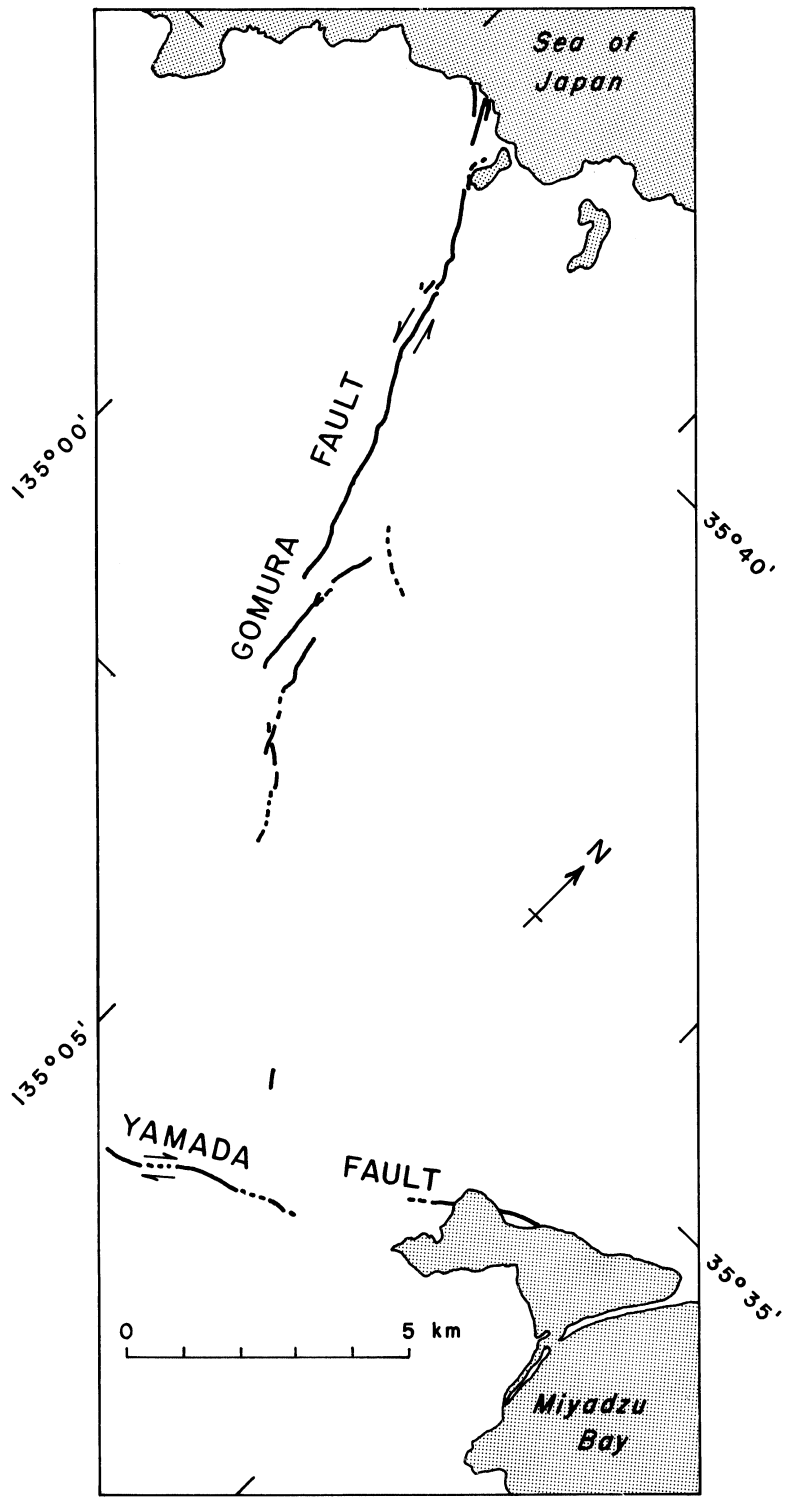

Figure 2. Surface faulting associated with the Tango, Japan, earthquake of 1927. From Yamasaki and Tada, 1928.

JAPAN 1930

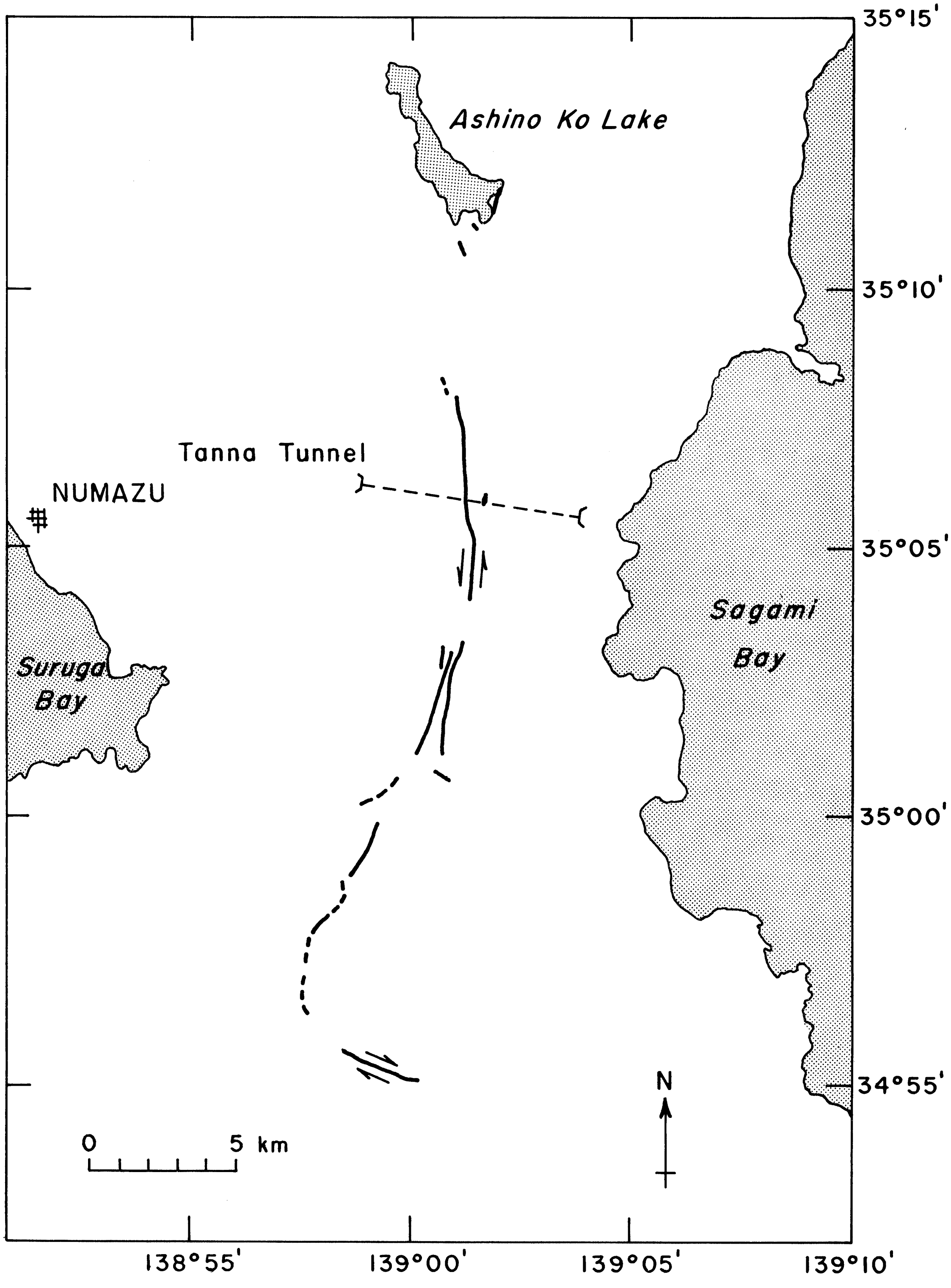

Figure 3. Map of Izu, Japan, faulting of 1930. Faulting inferred from discontinuous breaks or widely separated observations shown by dashed line. After Matsuda, 1972

The middle part of the surface faulting consisted of a double trace (fig. 3). The western trace was more nearly in line with the rest of the fault than the eastern trace but the latter had a greater left slip (3 m vs. 2 m). The two traces were as much as 1 km apart.

South of the approximately north-south main fault was a separate fault (fig. 3) that trended west-northwest. This fault had right slip displacement of about 1 m, in contrast to the left slip on the main fault; thus the two faults apparently had a conjugate relationship.

Offset streams and other topographic evidence show that geologically young displacements had occurred on the main fault prior to 1930 (Otuka, 1933; Kuno, 1936b), and Matsuda (1972, fig. 5) indicates that even the secondary ruptures occurred on faults with Quaternary displacements.

The fault was observed in the Tanna railroad tunnel 160 m below the surface. The rupture occurred along a breccia zone in the tunnel and had a left slip of about 2.4 m combined with a vertical displacement of about 0.6 m (Kuno, 1936a; Matsuda, 1972). At the ground surface above the tunnel the left slip was only about I m with a vertical displacement of about 0.5 m (Otuka, 1933, fig. 12). The section at the tunnel consists of about 45 m of sandy clay lake deposits overlying lower Pleistocene tuff, agglomerate, and lava flows (Nasu, 1931, p. 456; Kuno, 1936a).

Kuno (1936a, p. 101) indicates that the rupture in the tunnel had an en echelon arrangement and a more westerly trend with respect to the surface rupture; however, various strikes have been reported for the fault, both in the tunnel (Matsuda, 1972, table 3) and at the ground surface (Ihara and Ishii, 1932, fig. 1; Otuka, 1933, fig. 12) and whether the rupture in the tunnel was en echelon with respect to the surface trace is a moot question.

Tottori, Japan, September 10, 1943

This surface faulting near the Japan Sea coast of Honshu was associated with a magnitude 7.4 earthquake (Gutenberg and Richter, 1954). Similar maps of the surface faulting were published by Tsuya (1944) and Miyamura (1944). Two surface ruptures were found, a shorter northern one and a longer southern one; they converged at their northeast ends but did not join at the surface. The southern rupture was about 8 km long (Tsuya, 1944; Miyamura, 1944) and if one assumes that it extended in the shallow subsurface to join the northern rupture it could have been 14 km long at most. Maximum observed displacement at the surface was 1.5 m of right slip (Tsuya, 1944, table 3).

Triangulation data and aftershocks suggest that the rupture in the subsurface was longer than the surface rupture, and also longer than the known geologic faults. Movement of triangulation points between 1891 and 1957 has been attributed to the 1943 event and explained by assuming a fault some 35 km long that approximately parallels the surface faults (fig. 4). These data have also been interpreted as indicating right slip of about 2.5 m (Kanamori, 1972, p. 428-429), 1 m more than the maximum observed displacement on the surface faults. Aftershocks recorded within one month of the main shock were located in an area 40 km long by 20 km wide, the long dimension approximately parallel to and extending northeast and southwest of the surface faults (Omote, 1955, p. 649- 650). Kanamori (1972) notes that a cluster of epicenters at the western end of the aftershock zone was associated with a large aftershock and may not be directly associated with faulting in the main shock. Comparison of figures 2a and 3 of Kanamori (1972) shows that the aftershock locations of Omote extend about 10 km farther southwest than the fault inferred from the triangulation. The subsurface faulting inferred from the triangulation and aftershock studies extends both northeast and southwest of the surface faulting and into areas of Cretaceous and Tertiary bedrock where no geologic fault is recognized. Figure 5 shows the surface faulting and the approximate trend of the fault inferred from triangulation. The northeast end of the straight part of the inferred fault is at point A; it extends westward through point B and about 5 km west of the border of the map. As can be seen on figure 5, the inferred subsurface fault extends into bedrock areas where no geologic fault is known. The same lack of geologic faults beyond the 1943 surface ruptures is also shown on the 1/50,000 scale geologic map of Murayama and others (1963). Geologic mapping whose purpose is not specifically the identification of active faults can sometimes miss subtle evidence of faulting (Bonilla, 1975) and thus it is possible that the geologic fault at the surface actually does extend beyond the limits shown on the cited maps; however the map of Kakimi and others (1978) shows no Quaternary faulting beyond the 1943 ruptures, and Matsuda (1977, table 1) indicates that essentially the whole length of the Quaternary fault ruptured in 1943.

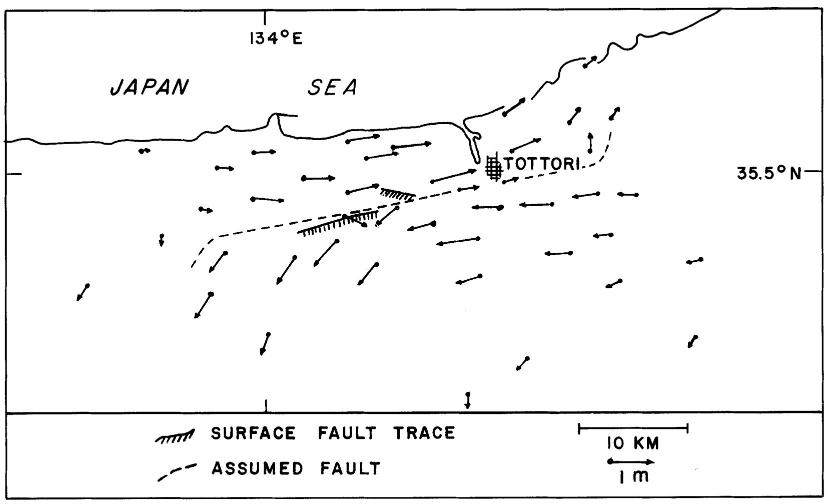

Figure 4. Surface faulting (generalized) in the 1943 Tottori, Japan, earthquake, and fault inferred (dashed line) from displacement of triangulation points in the period 1891-1957 (arrows). After Kanamori, 1972, figure 3.

Gerede, Turkey, February 1, 1944

This strike slip faulting, which was associated with a magnitude 7.4 earthquake (Gutenburg and Richter, 1954), extended for about 180 km along the Anatolia fault and the maximum observed right slip was 3.5 m. The most detailed published map (Ambraseys, 1970) shows subparallel traces which are about 4 to 6 km apart (fig. 6). This is the greatest stepover reported for the main trace of any historic strike slip surface rupture. Unfortunately this faulting was not well documented; displacement was measured at only two places according to Ambraseys and Zatopek (1969) and considerable doubt remains as to the locations of the actual surface breaks.

Gobi-Altai, Mongolia, December 4, 1957

Surface faulting associated with a magnitude 8.0 earthquake (Okal, 1976) extended for 265 km and had a maximum left slip of 8.85 m, the largest strike slip measured immediately after any historic surface rupture. Over most of its surface outcrop the rupture had a reverse component, with the south side uplifted. Focal mechanism solutions (Florensov and Solonenko 1963; Okal, 1976; Chen and Molnar, 1977) indicate left slip with a reverse component on a plane dipping about 40° to 50° south. The dips at the surface were in general substantially steeper however, judging by photographs of the-fault, the locally vertical dip of mylonites along the fault, and the cross sections of Florensov and Solonenko (1963, p. 353, figs. 185, 186, and Appendix II) which show southward dips of 68° to 88°.

The subsidiary surface ruptures in this event were notable for their abundance, displacements, and distance from the main fault. About 35 tectonic subsidiary ruptures occurred; most of them were on the hanging wall side of the fault but they also occurred on the footwall side. The Tormkhon branch fault had a maximum vertical (reverse) displacement of 9.2 m, a larger displacement than the maximum 8.85 m strike slip on the main fault nearby. The most distant secondary fault was 24 km from the main fault and had a vertical (reverse) displacement of 7 to 8 m along with a right slip component of unspecified amount (Florensov and Solonenko, 1963, Appendix II, p. 360). Secondary faulting occurred at a greater distance (about 30 km) from the 1976 strike slip Guatemala fault but the displacement was less than 0.5 m (Bonilla and others, 1976).

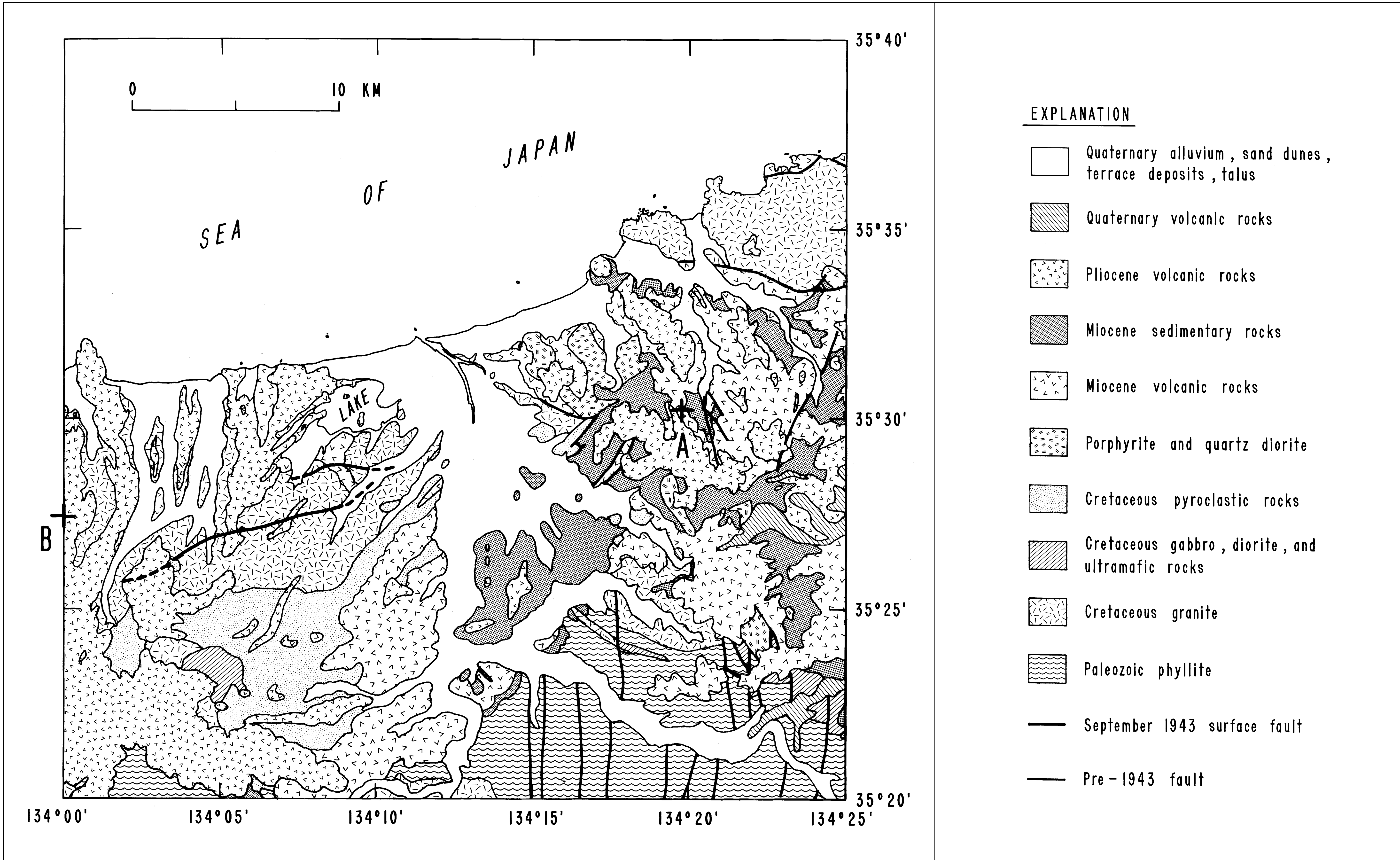

Figure 5. Geologic map of the Tottori, Japan, area showing surface faulting of 1943. Points A and B (marked with plus signs) are on the fault inferred from triangulation. Geologic map generalized from Uemura and others, 1974.

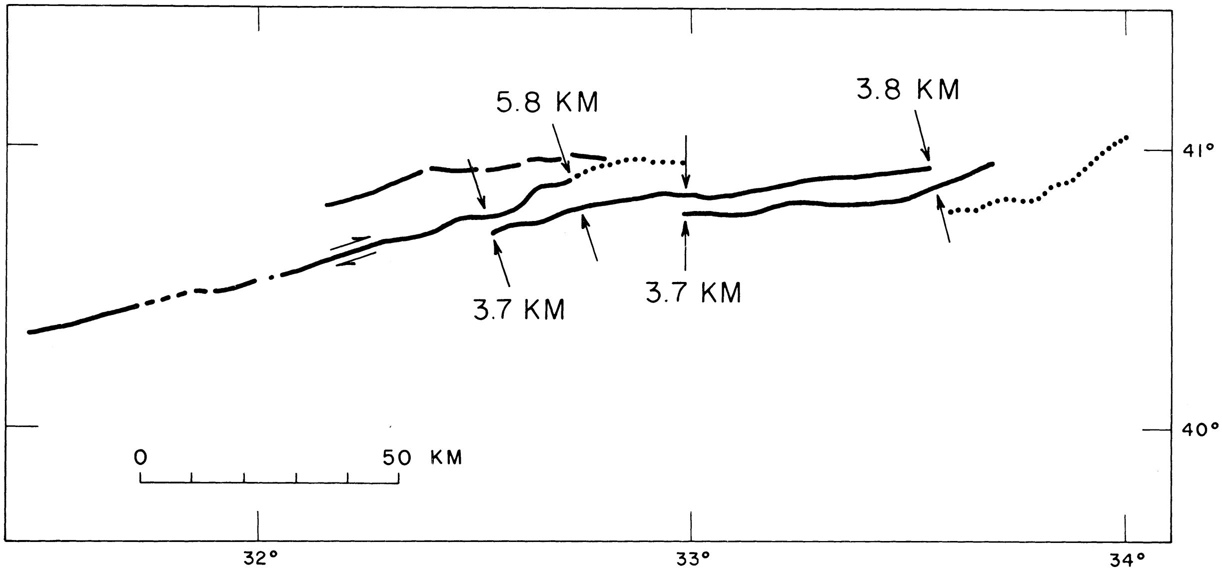

Figure 6. Map showing approximate location of part of the 1 February 1944 surface faulting in Turkey. Dotted lines show some of the faults that were in existence before the earthquake. The locations of the traces are not well documented. From Ambraseys, 1970, fig. 6.

Most of the Gobi-Altai surface faulting occurred on preexisting faults but some is reported to have been new faulting. The main rupture occurred along a fault which locally had pre-1957 scarps (Florensov and Solonenko, 1963, p. 350-352), and the general position of the fault is quite visible on LANDSAT imagery. The Bakhar graben was formed along one 15 to 20 km segment of the main fault. The northern rupture of the graben was along a preexisting fault which in places had a scarp 3-8 m high, but the southern rupture was a new fault according to Florensov and Solonenko (1963, p. 281, 321, 350). The distance between the old and new bounding faults of the graben is 300-800 m, and the intervening ground was disturbed to various degrees by other faults and fissures. The Tormkhon branch fault, which had a vertical displacement of 9.2 m, is said to be a newly-formed fault (Florensov and Solonenko, 1963, p. 364); however this is doubtful because two geologic maps show distinctly different formations in contact along much of the fault (Florensov and Solonenko, 1963, Appendix I and fig. 153). At least four other subsidiary faults are indicated by map symbol as new faults, but details are not given (Florensov and Solonenko, 1963, Appendix II).

Hebgen, Montana, August 17, 1959

This normal faulting, about 25 km long, was associated with a magnitude 7.1 earthquake. The fault pattern was quite irregular, the strikes ranging through almost 90° (fig. 7); seismological evidence suggests that the event was a double shock (Ryall, 1962, p. 268-270), which may account for some of the complexity of the faulting. The faulting consisted of curved and straight portions that made up the Red Canyon and Hebgen Lake fault segments. Displacements on these two, which can be considered as constituting the main fault at the surface, was 5 to 6 m, much greater than the displacements (less than 1 m) on the numerous subsidiary faults. The subsidiary faults were distributed over a wide area, three of them (A, B, and C, fig. 7) being 13 km from the main fault.

All of the surface ruptures, including the subsidiary ones, seem to have been on preexisting faults or monoclines some of which had had many prior displacements (Witkind, 1964, p. 38-43; Myers and Hamilton, 1964, p. 62); however in a few places where the ruptures are in bedrock, evidence for previous faulting is problematical and the suggestion has been made that the faults increased in length in 1959 (Myers and Hamilton, 1964, p. 85-86). Additional comments on this are in a following section.

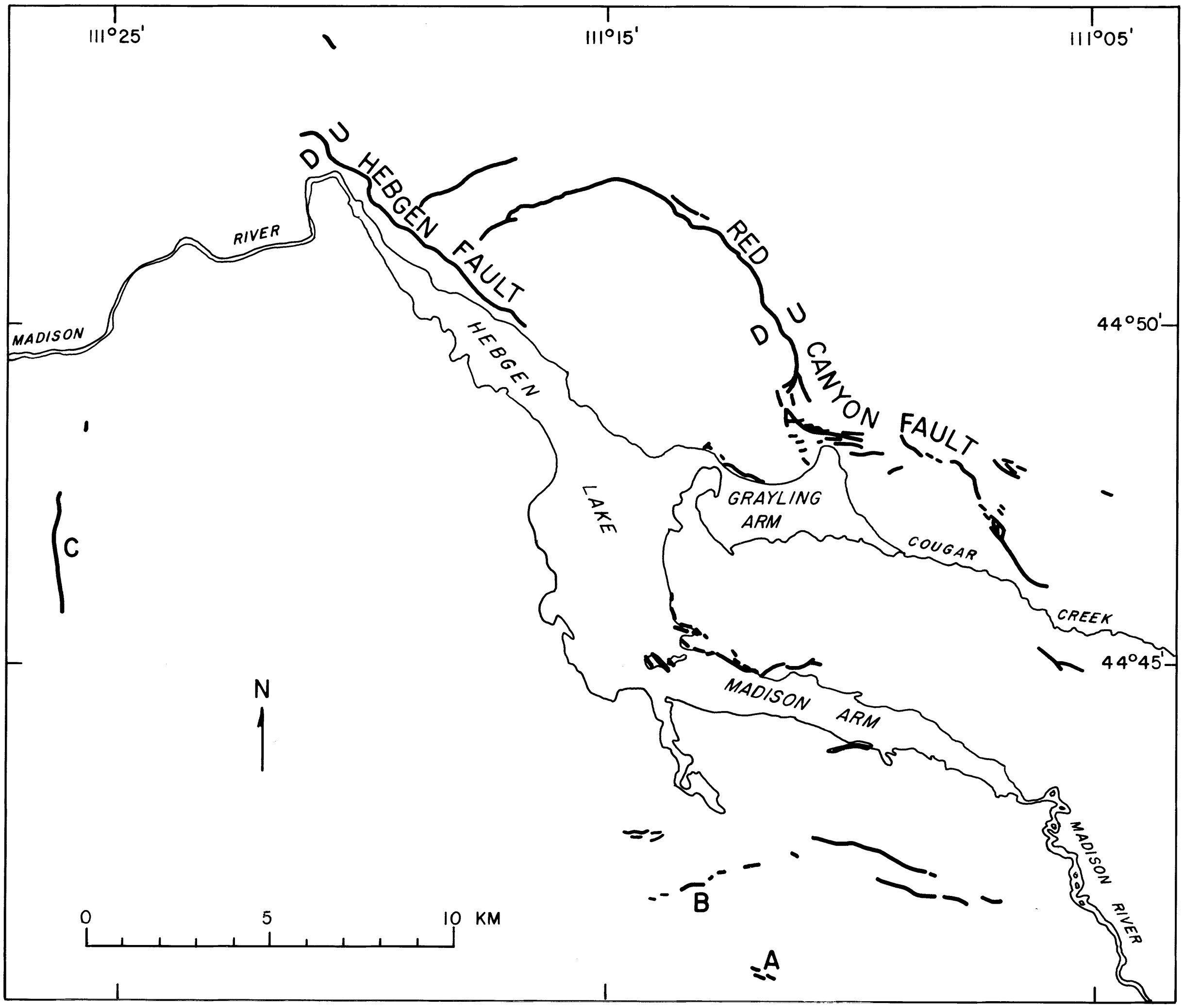

Figure 7. Surface faulting (heavy lines) in the Montana earthquake of 1959. From Myers and Hamilton (1964) and Witkind (1964).

There is a difference of opinion as to whether the surface faulting in 1959 was the cause of or only secondarily related to the earthquake. Myers and Hamilton (1964, p. 97) believe that the surface effects can be viewed as slumps, of various scales and at different depths, resulting from movement on a deep structure that may be a normal fault or an abrupt monocline trending N. 80°W. (the Hebgen and Red Canyon faults taken together trend about N.58°W.). Reactivation of these faults, which have had many previous displacements, is considered by Fraser, Witkind, and Nelson (1964) to be more or less directly the cause of the earthquake. Focal mechanism solutions indicate a normal fault trending about N.80°W. and dipping 54° to 64°S. (Ryall, 1962;

Dewey and others, 1972; Smith and Sbar, 1974). Aftershocks of magnitude 4 or greater within one year of the main shock are in an east-west zone about 80 km long which, however, is athwart many northwest-trending faults (Dewey and others, 1972). Detailed and much more precise monitoring of earthquakes in 1972 shows an active zone 80 km long and up to 20 km wide trending N.80°W.; however in detail the zone is made up of en echelon northwest-trending zones, two of which are approximately in line with southeastward projections of the Hebgen and Red Canyon faults (Trimble and Smith, 1975). Additionally, Trimble and Smith (1975, p. 736-737) show a cross section approximately perpendicular to the Hebgen fault which shows a seismically active zone associated with this fault, extending from near-surface to 15 km depths and dipping 70°S.; they estimate a precision of about ±1.0 km for epicenters and ±2.0 km for focal depths. The surface ruptures are adequate to account for the size of the earthquake (magnitude 7.1, Pasadena). Estimating seismic moment from the surface fault displacements and lengths and converting to magnitude using $M = 2/3 \log M_o - 10.7$ (Hanks and Kanamori, 1978) yields magnitudes ranging from 6.9 to 7.2. The smaller magnitudes result from using median surface displacement and the larger magnitudes from using 3/4 of the maximum surface displacement. The geological and seismological evidence, part of which has been reviewed here, is far from conclusive but on balance it seems to favor the interpretation that the Hebgen and Red Canyon faults represent the causative faults for this earthquake.

Meckering, Australia, October 14, 1968

This surface faulting in the Precambrian granite and gneiss of Western Australia accompanied an earthquake of about magnitude 7. An arcuate fault 37 km long, the strike ranging through 90°, was visible in weathered bedrock covered by 1 m or more of sand and clay (Gordon, 1971a). The faulting was of reverse type with a right slip component, and the maximum net slip was about 3 m. The main fault consists of a series of arcs joined by straight segments as much as 1.6 km long (fig. 8). On the downdropped side are some subsidiary faults with displacements of as much as 0.7 m and lengths up to about 7 km. The uplifted side was cut by a northeast-trending straight fault about 17 km long that had a right slip displacement of as much as 0.2 m (Gordon, 1971b). To the east of this fault were many minor faults, generally with downthrow to the west; because displacements were very small they could be seen only on compacted surfaces such as roads, and their full extent is not known (Gordon, 1971a).

A focal mechanism solution for this earthquake indicated reverse slip with a left slip component on a fault striking N.28°W. and dipping 68°N.E. (Fitch and others, 1973). The surface fault was arcuate in plan so that assignment of a generalized strike is difficult, but a cord joining its ends trends about N.12°E., and less than one third of the fault has a strike as westerly as N.25°W. Dips measured at the surface were to the southeast, east and northeast, and ranged from 15° to 55°, with a modal value of about 40°; fractures on the hanging wall side suggest that the dip increases with depth (Gordon, 1971a). The disagreement between the focal mechanism solution (left reverse slip on a northwest-trending fault) and the surface faulting (right reverse slip on a north or northeast-trending fault) is substantial. According to Fitch and others (1973, p. 348-349) the P-waves strongly suggest a multiple rupture, which may account for the complexity and wide range in strike of the surface faults.

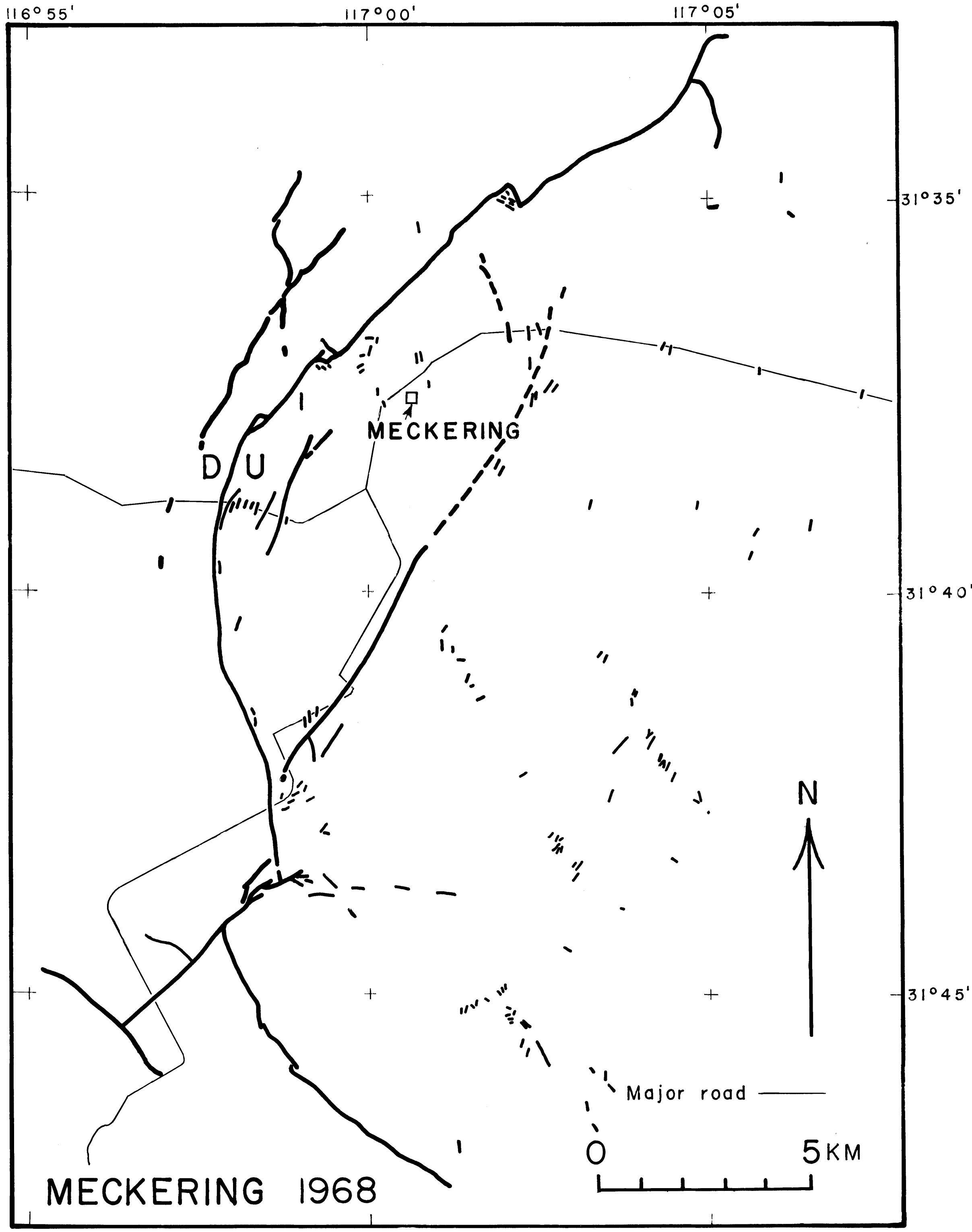

Figure 8. Surface faulting near Meckering, Australia, 1968. Short thin lines are minor faults, most of which are downthrown to the west; they were visible only on hard surfaces such as roads. From Gordon, 1971a, figures 2 and 6.

Gediz, Turkey, March 28, 1970

Surface faulting accompanied an earthquake of about magnitude 7.2 in western Turkey on March 28, 1970. The principal surface trace was about 39 km long (including gaps as long as 2 km where no faulting was recognized), and its strike ranged from east-west in the southeast part through northwest to about north-south in the northern part (fig. 9). For convenience in the discussion that follows, the northwest trending part will generally be considered as a segment of the "north-south" part of the fault. Secondary faults occurred in various places and were especially numerous to the east of the north-south part of the main fault. Vertical displacements predominated; they were of normal type with the larger displacements (maximum 2.2 m) on the north-south part of the fault (Ambraseys and Tchalenko, 1972, figs. 9 and 10; Tasdemiroglu, 1971, table 3). Left-lateral displacements, generally less than 0.4 m, were noted at many places on the main fault both by Tasdemiroglu (1971) and Ambraseys and Tchalenko (1972, figs. 9 and 10). Near the southeast end of the main fault, where it forms a peculiar northward salient, unusual right-lateral displacements ranging up to 0.8 m were seen on a northeast- trending segment about 1 km long.

The surface fault cut various types of consolidated rocks. The generally north-south part was in crystalline limestone, and Neogene volcanic and sedimentary rocks; the generally east-west part was in Neogene sediments, serpentine, and limestone; and in various places the traces followed the contacts between Neogene sediments and crystalline limestone, schist, or serpentine, or between serpentine and crystalline limestone or schist. Dips measured by Ambraseys and Tchalenko (1972) where the fault cut limestone were 65° to 70°E. on the north-south part and 60° and 65°N. on the east-west part. The relation of the trace to topography also indicated a northward dip of 60° for part of the east-west segment (fig. 9). In several places the investigators (Tasdemiroglu, 1971; Ambraseys and Tchalenko, 1972) found evidence for pre-1970 faulting including faulted contacts, striated fault planes, and scarps.

Aftershocks of the March 28, 1970 earthquake fall in a northwest-trending zone (Dewey, 1976; Jackson and Fitch, in press). If an isolated group of aftershocks in the northwest part of the area is included the zone is about 60 km long and trends about N.55°W.; if the isolated group of aftershocks in not included, the zone is about 40 km long and trends N.64°W. Focal mechanism solutions for the main shock yield a strike of about N.50°W. and a dip ranging from 30° to 35° northeast, with the strike possibly being more northerly than N.50°W. (Dewey, 1976; McKenzie, 1978; Jackson and Fitch, in press). Thus the strike of the focal mechanism for the main shock has a somewhat more northerly trend than the aftershock zone, particularly if the isolated group of aftershocks is excluded, and is at a high angle to both the north-south and east-west parts of the surface faults. Focal mechanisms of three aftershocks within one month of the main shock indicate strikes ranging from N.76°W. to N.83°W. (McKenzie, 1978), strikes that are more westerly than the trend of the aftershock zone and more northerly than the east-west part of the surface faults. Various dip angles were also obtained from the focal mechanism solutions. The indicated dip for the main shock was 30°-35° northeast; for an aftershock the same day, 58 north; for an aftershock April 16, 31° northeast; and for an aftershock on April 19, 66° northeast (Dewey, 1976; McKenzie, 1978). Thus, compared to the 60° to 70° dips measured on both the north-south and east-west parts of the surface faults, the focal mechanisms indicate a much lower dip for the main shock and the April 16 aftershock, but similar dips for the March 28 and April 19 aftershocks.

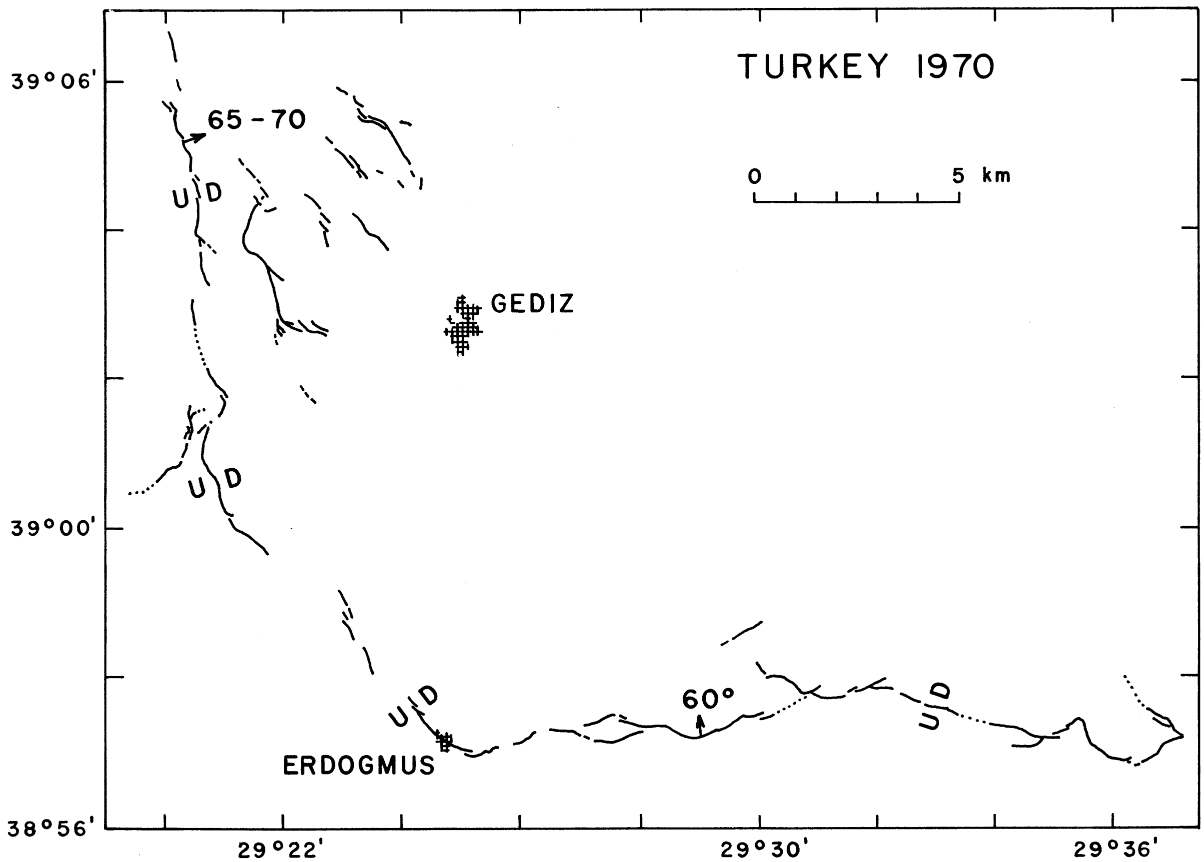

Figure 9. Surface faults associated with the Gediz, Turkey, earthquake of March 28, 1970. From Ambraseys and Tchalenko, 1972.

The surface faulting and the focal mechanism solutions both indicate normal faulting of a complex sort. The sequence of events and the relation between the surface and subsurface faulting is not at all clear. The minor but persistent left slip component observed on both the north-south and east-west trending parts of the surface faults together with normal slip downward of the east and north sides respectively show that the downthrown block did not behave as a single unit. Perhaps the north-south and northwest trending parts of the surface faults were associated with the main shock, and the east-west trending part was associated with the aftershock the same day which, according to the focal mechanism solution, had a strike of N.83°W. The time of this aftershock is not given by McKenzie (1978) but presumably it is the one listed by Dewey (1976, p. 848) that occurred two hours after the main shock and had a body wave magnitude of 5.2. Statements of witnesses (Ambraseys and Tchalenko, 1972, p. 250) show that the faulting at the southeast end of the northwest-trending part of the surface fault (at Erdogmus) occurred during the main shock, but the published reports do not mention the time of rupture for other parts of the surface fault. Based on indirect evidence Ambraseys and Tchalenko (1972, p. 242) suggest that afterslip increased the displacements on the faults.

In addition to the events described above, other examples could be given of en echelon, parallel, irregular, branching, and conjugate faults. Although both of the normal faults described above had an irregular map pattern, other normal faults were rather straight (e.g., California, 1950; Nevada, 1915), with marked changes in strike limited to local segments. The Nevada faulting of 1915, according to the field investigations of R. E. Wallace (written communication, 1977), included displacement on the China Mountain trace, which had a stepover distance of about 6.5 km from the next en echelon trace. Notable also was the Rikuu, Japan, faulting of 1896 in which two subparallel reverse faults 10 to 18 km apart broke the surface (Yamasaki, 1900; Imamura, 1930; Kobayashi, 1976). A stepover of 1.3 km occurred between the Sylmar and Tujunga segments of the 1971 San Fernando reverse fault zone (U.S. Geological Survey, 1971).

Relation Of Surface Rupture To Subsurface Rupture

In this section comparisons are made between historic faulting mapped at the surface and concurrent faulting inferred in the subsurface. The nature of faulting in the subsurface is based on seismological or geodetic data and on a few observations in tunnels and other openings. As permitted by the data, comparisons are made of surface and subsurface fault length, displacement, type, and orientation; some comparisons of this kind have already been made in the preceding section. Subsurface seismogenic faulting, as inferred from seismological and geodetic data, has usually been expressed at the surface in one of the following ways: 1) no faulting observed; 2) arching or other broad deformation with a few subsidiary faults here and there; 3) surface rupture shorter than subsurface rupture; and 4) surface rupture substantially the same length as subsurface rupture. A fifth category, in which the surface rupture is longer than the earthquake-related subsurface rupture, could occur on faults subject to tectonic creep, but whether this has actually happened is not clear. Inasmuch as mapping of surface faults is usually done several days or weeks after the related earthquakes, strict syncroneity between surface and subsurface faulting is not assured, but approximate concurrence is assumed in the descriptions that follow.

The first category includes large shallow-focus events in which no faulting appears at the surface. An outstanding example of this is the Kita-Mino, Japan, event of August 19, 1961. This earthquake of magnitude 7.0 was investigated in the field by Morimoto and Matsuda (1961). Although they found a geologically young fault (the Hatogayu-Koike fault) in the epicentral area, no near-surface faulting related to the 1961 earthquake could be found, even in aqueduct tunnels that crossed the fault. Leveling across the projection of the fault detected a few centimeters of differential movement over a broad zone. A study of the seismological and leveling data was done by Kawasaki (1975) who concluded that the data best fit a subsurface rupture on the Hatogayu-Koike fault. The modeled rupture had a length of 12 km, a width (down-dip dimension) of 10 km, an average right reverse oblique slip of 2.5 m, a dip of about 60°, and extended to within 2 km of the surface.

The Fukui, Japan, earthquake of 1948 is another example of a large shallow earthquake with no visible surface faulting. This magnitude 7.3 earthquake (Gutenberg and Richter, 1954) was associated with a zone of fractures 27 km long consisting of cracks that paralleled the zone and did not have an en echelon pattern (Nasu, 1950, p. 116). Neither dip slip nor strike slip were detected on the fractures, but triangulation and leveling across the zone indicated a combination of left slip and vertical displacement. P-wave first motion analysis and the triangulation data suggest about 2 m of left slip on a vertical fault (Kanamori, 1973) and leveling showed as much as 0.7 m of vertical displacement measured between points about 2 km apart (Nasu, 1950). The lack of clear-cut faulting at the surface has been attributed to a thick cover of unconsolidated sediments (Nasu, 1950, p. 115-116). Despite the lack of distinct faulting at the surface, damage to roads, houses, telephone and power lines, and the railroad was notable along the zone of surface fracture (Nasu, 1950, p. 116-118).

The second category includes events in which the main fault is expressed at the surface in the form of arching or similar broad deformation, with a few subsidiary faults here and there. The Hawke's Bay, New Zealand earthquake of 1931 was of this kind. A magnitude 7 3/4 earthquake (Gutenberg and Richter, 1954) was associated with an elongated asymmetric dome of uplift about 100 km long and 15 to 20 km wide; maximum uplift was about 2-3 m (Henderson, 1933; Wellman, 1970, p. 42-43). Along a small part of the steep side of the uplift, or slightly off of it, a series of faults broke the surface in a zone about 10 km long. They were low-angle, bedding plane faults generally parallel to the axis of uplift and had a reverse-slip displacement of about 2 m. The concealed fault, part of whose course was under the sea, was inferred to be an eastward-dipping reverse fault (Henderson, 1933) and the position of the epicenter (Bullen, 1938) supports this inference.

The Inangahua, New Zealand faulting of 1968 seems to fall in this category also. The major 1968 surface faults were the north-trending Inangahua trace, a little more than 1 km long with a left reverse displacement of 0.5 m, and the northeast-trending conjugate Rotokohu trace, somewhat more than 1.5 km long with a right reverse oblique slip of nearly 2 m. A dome of uplift elongated in a north-northeast direction also formed; to the east was a narrower zone of subsidence. Surveys did not cover the whole area of uplift but extrapolation of the data suggests a length of about 35 to 40 km and a width of about 25 km (Lensen and Otway, 1971, fig. 2). The Inangahua trace was west of, and the Rotokohu trace on, the crest of the uplift. The aftershocks recorded in 1968 (Adams and Lowry, 1971) and in 1972 (Robinson and others, 1975) approximately coincided with the zone of vertical deformation. The length of both the uplifted area and the zone of early and late aftershocks compared to the length and positions of the Inangahua and Rotokohu traces suggest that the surface traces were secondary faults related to a much longer concealed fault that was expressed at the surface primarily by uplift.

In the third category the surface rupture, even though on the seismogenic fault, is shorter than the subsurface rupture as inferred from seismological or geodetic data. The Tottori, Japan, earthquake of 1943 in which the surface faults were no more than 14 km long but the subsurface rupture was probably about 35 km long has already been described. Another example is the Kern County, California, faulting of 1952. The ground near the epicenter was shifted about 0.6 m to the northwest (Whitten, 1955, fig. 4) and some short, probably secondary, faults were observed; but the nearest rupture that represents the main fault was about 23 km to the east. In the 23 km gap no surface ruptures were found (Buwalda and St. Amand, 1955) but arching of the ground surface of about 0.6 m, 7 km east of the epicenter, was detected by leveling (Lofgren, 1966). The eastern zone of ruptures extended discontinuously for about 30 km. Thus the subsurface faulting extended eastward from the epicenter for 53 km but the fault broke the surface for only about 30 km of the eastern part.

Another example in which the surface fault length was shorter than the subsurface fault length is the Izu-Hanto-oki, Japan, earthquake of 1974. The surface rupture on land was 6 or 7 km long (Matsuda and Yamashina, 1974; Kakimi and Kinugasa, 1976) but intersected the shoreline at its southeast end. Aftershocks recorded within 22 days after the main shock (Nakamura and others, 1974, fig. 7; Karakama and others, 1974, fig. 7) occurred in a zone about 25 km long, some 7 km of which was offshore to the southeast (Karakama and others, 1974, fig. 7). The surface rupture thus may have been 14 km long, including 7 km offshore to the southeast, but the aftershocks suggest that the subsurface rupture extended another 10 km or so to the northwest where no surface rupture occurred. A vertical section along the fault showing foci of aftershocks (Karakama and others, 1974, fig. 8) does not show an increase in focal depths to the west.

In the fourth category the mapped surface rupture and the inferred subsurface rupture are substantially the same length. Well documented examples of this group are the 1968 Borrego Mountain, California, strike-slip faulting (Hamilton, 1972; Wyss and Hanks, 1972), and the 1971 San Fernando, California, reverse faulting (Allen, Hanks, and Whitcomb, 1975; Savage and others, 1975).

Relation Of Surface Rupture To Preexisting Faults

Of the main faults in 108 examples of worldwide historic surface faulting on land, 91 percent occurred or probably occurred on preexisting faults, 8 percent are indeterminate in this regard based on available data, and 1 percent (1 example) apparently occurred where no fault existed previously. In a few other cases the main or subsidiary faults apparently penetrated unbroken materials to a limited extent. The correspondence in position of the historic ruptures with prehistoric ruptures has ranged from exact to approximate, and in places the surface rupture has elected to follow one of two or more available preexisting faults.

Most historic ruptures have occurred on faults that show clear evidence of Quaternary displacement in the topography or stratigraphy; several examples of these have been described above. Some faults have had more than one historic displacement on some segments and a few are reported as being exactly on the earlier break. The 1906 rupture on the San Andreas fault extended through parts of the fault that had a small displacement in 1890 (Lawson and others, 1908) and apparently a large displacement in 1838 (Louderback, 1947). Ruptures occurred on the San Andreas fault in the Parkfield-Cholame area in 1857, 1901, 1922, 1934, and 1966, the 1966 rupture being about 8 m from the 1934 rupture at one place (Brown and Vedder, 1967). The Rainbow Mountain, Nevada, faulting of August 1954 partly coincided with and partly extended the July 1954 faulting (Tocher, 1956). The Imperial California faulting of 1966 coincided with part of the 1940 faulting (Brune and Allen, 1967). Repeated ruptures have occurred on parts of some faults in Turkey: the faulting of 1970 partly coincided with the faulting of June 25, 1944 (Ambraseys and Tchalenko, 1972, p. 247; Tasdemiroglu, 1971, p. 1521); the principal faulting of 1951 on the Anatolian fault followed the trace of the February 1, 1944, faulting (Pinar, 1953); and the easternmost 25 km or so of the July 22, 1967, faulting overlapped the 1957 faulting on the Anatolian fault (Ambraseys and Zatopek, 1969).

Historic surface faults commonly follow preexisting faults, some indicated by gouge or breccia zones, but they seem to be quite selective when several choices are available. As described above, the 1927 strike-slip Gomura fault at one locality followed one clay-filled fissure but another one with a different orientation 2 m away was not utilized. In the 1971 California faulting the Oak Hill reverse fault at one trench site followed a preexisting fault but did not affect a similar fault 1 m away (Bonilla, 1973). At one place the strike slip Izu-Hanto-oki, Japan, faulting of 1974 followed a narrow fault but a wider and more impressive fault only a few meters away showed no displacement (Matsuda and Yamashina, 1974). Although some of the August 1954 Rainbow Mountain, Nevada, normal faulting coincided with the July 1954 fault, some of it was subparallel to the July fault (Tocher, 1956). Comparison of the traces of the December 1954 Fairview Peak, Nevada, normal faulting with a somewhat generalized map of the 1903 normal fault traces in the same area (Slemmons and others, 1959, topographic map) shows that the two traces in that area coincided in a few places, but were more than 60 m apart in many other places. Reverse faulting on the Patton Bay fault in 1964 (Plafker, 1967) followed a previously recognized fault scarp (Condon and Cass, 1958) over most of its length but at the south end of Montague Island the 1964 rupture, instead of following the prominent scarp which veered westward, took a straighter course and was as much as 2 km from the scarp where it passed out to sea. This straighter course also followed a preexisting fault which may have had pre-1964 Holocene displacement on it (Plafker, 1967). The selectivity of the 1891 Japan faulting is apparent on figure 1. That rupture followed certain parts of preexisting faults but not others; as seen on the figure the historic rupture failed to follow two faults to their ends and instead stepped over 2 to 3 km to follow other faults. A similar selectivity was apparent in the 1930 North Izu faulting where two subparallel preexisting faults in the central part of the fault zone were utilized but only one of several subparallel faults near the south end showed displacements in 1930 (Matsuda, 1972).

Historic surface faulting that is considered to be new is quite rare. The most impressive example is the Rotokohu trace of the Inangahua, New Zealand, faulting of 1968. This secondary fault had a maximum right reverse oblique slip of nearly 2 m and was more than 1.5 km long. The terrace deposits of the last glaciation had not previously been faulted at that place according to Adams and others (1968, p. 788) and the stratigraphic relations do not require a fault in the underlying Tertiary sediments. The Rotokohu trace and concurrent faulting at Rough Creek (vertical displacement 1.8 m, length about 0.5 km) are considered to be bedding plane faults; the available evidence suggests that they are new faults (Lensen and Suggate, 1968; Lensen and Otway, 1971; Lensen, 1970), although a limited amount of bedding plane slip could have occurred during folding prior to 1968 (R. P. Suggate, written com., 1975).

Another example of new faulting occurred near Matsushiro, Japan, in 1966 and continued at varying rates until 1968 or longer (Nakamura and Tsuneishi, 1967; Tsuneishi and Nakamura, 1970). The displacement at the surface occurred as tectonic creep with a few small (less than 5 cm) sudden displacements. The faulting was preceded and accompanied by thousands of earthquakes, the largest of which was of about magnitude 5. The surface fractures were in a series of en echelon zones occupying a belt about 500 m wide and 3 km long, but deformation of structures and triangulation data indicate a length of about 7 km for the faulting in the subsurface. Displacement across the zone was about 0.5 m of left slip and 0.3 m of opening. No great faults exist along the zone of surface faults or the surrounding area and no evidence of pre-1966 Holocene displacement was found. The zone of earthquake faults developed in alluvial fans, but outcrops of Tertiary bedrock, where important prior faulting would be evident, cross the trend of the zone of faults on both ends. A fault was recognized in the bedrock, but it is about 0.8 km from and subparallel to the earthquake fault zone, and has been inactive since middle Pliocene (Matsuda, 1967).

Possible new faulting in the Mongolian earthquake of 1957 has been described above. The Tormkhon branch fault, although referred to as newly-formed, probably was a rejuvenation of an older fault. The southern bounding fault of the Bakhar graben may have been new, as well as some of the minor faults, but the data at hand do not permit critical evaluation of these possibilities.

Some new faulting may have occurred locally in the 1959 Montana event. The Hebgen fault scarp is interrupted by a limestone knob. "As these scarps approach the large but discontinuous limestone outcrops from both sides, they break up into a number of small scarps. The bedrock of the ridge is shattered by a complex of fissures and small extremely irregular faults, dropped down on either side; where these breaks cut nearly continuous outcrops, there is no clear evidence for older displacements." (Myers and Hamilton, 1964, p. 85). This may be an example of a fault "barrier" in the sense of Das and Aki (1971) which was only partly broken through.

The Meckering, Australia, event of 1968 included some new faulting. About 1 km from the main fault and on its upthrown side a fault about 200 m long formed in strong unweathered granite. The fault is vertical, had a tensional opening of about 9 mm and a right slip of about 3 mm (Gordon, 1971a, p. 90 and fig. 10).

Another example is provided by the Coyote Creek faulting of 1968. The northernmost part of the 1968 fault, consisting of en echelon fractures in a zone as much as 45 m wide, took a middle course between two preexisting faults and extended a few hundred meters into Pleistocene deposits where no earlier break could be seen (Sharp and Clark, 1972, p. 132).

Summary

Map patterns in historic surface faulting can be described as single, en echelon, parallel, conjugate, branching, and irregular. En echelon and parallel breaks commonly occur on strike-slip faults and a few examples are known for normal and reverse faults. Stepovers (the perpendicular distance between en echelon or parallel traces) for strike slip faults range up to 3 km at least, and in one example stepovers of 4 to 6 km have been reported. Stepovers in normal faults have ranged up to at least 4 km, and probably to 6.5 km. Stepovers in reverse faults have been as much as 1.3 km. A few conjugate faults have been reported on strike-slip faults and at least one example is known for subsidiary faults in a reverse fault event. Branching faults are rather uncommon but they have been associated with strike slip, normal, and reverse faults; typically they are rather short. Irregular map patterns, in which the strike of the fault has a wide range, have occurred on reverse and normal faults. Subsidiary ruptures associated with dip slip faulting, although more common on the upthrown sides of reverse faults and the downthrown sides of normal faults, have occurred on both sides of both types. Displacements large enough to damage structures have occurred on subsidiary faults as far as 24 to 30 km from the main fault, but subsidiary faulting at such distances is uncommon.

Considering only cases where some faulting or notable warping has occurred at the surface, the relation between surface and subsurface rupture (the latter inferred mainly from seismological and geodetic data) has varied greatly. The shallow-focus magnitude 7.0 Kita-Mino, Japan, earthquake of 1961, estimated to have 2.5 m of reverse oblique slip, did not break the surface and only produced small vertical changes detected by leveling. In another event, involving strike slip with a subordinate vertical component, a narrow zone of parallel fractures without noticeable dip slip or strike slip appeared on the ground surface above the buried fault. In some earthquakes the surface faulting is directly related to the causative fault but the surface length is less than the subsurface length; however, contrary to what would be expected from a penny-shaped break, the surface rupture is not necessarily near the midpoint of the subsurface rupture. In one event (Tottori, Japan, 1943) the subsurface rupture was not only longer than the surface rupture but apparently also longer than the geologic fault at the surface. Four possible explanations come to mind for this: 1) the full extent of the geologic fault at the surface may not have been recognized; 2) the surface geology (which includes Cretaceous granites and Tertiary volcanics) is decoupled from the geology at depth; 3) as in several other historic events, only part of the subsurface faulting intersected the ground surface and the same pattern occurred repeatedly in the past, producing the short Quaternary fault at the surface; and 4) new faulting occurred, extending the preexisting fault. Additional investigations are needed in order to make a choice among these possibilities.

The great majority of the historic surface ruptures on the main fault have occurred on preexisting faults, a few are indeterminate in this regard and one new main fault (Matsushiro, Japan, 1966) has been reported. Many historic subsidiary ruptures have occurred on preexisting faults, but for most of them such information is not known. New faulting has also occurred as subsidiary faulting and, locally, main faults have extended themselves for short distances. In one event (Hebgen, Montana, 1959) the reported new faulting seems to have advanced into a "barrier" on the fault. Subsurface faulting at Tottori, Japan, in 1943 extended beyond the known geologic fault at the surface; this may be an example of a fault extending itself but is not the only possible explanation.

Although historic surface faulting has typically followed preexisting faults, it has been selective, following one fault for a distance then stepping over as much as 6.5 km to another fault. On a more detailed scale, displacement has ocurred on one fault in preference to another as close as a few meters away. One can speculate that the choices among available paths depends on orientations of the preexisting faults with respect to stress and their relative strengths.

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