fil Brothers Fault Zone

Strike-slip faulting terminates the Basin and Range province in Oregon

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ABSTRACT

The pattern of faulting in southeastern Oregon is interpreted in terms of four major zones of right-lateral strike-slip faulting that separate blocks broken by normal faulting. The total amount of east-west extension is considered to decrease in the block north of each strike-slip fault zone. The right-lateral offset results from the decrease in extension. Extension essentially dies out across the northern two fault zones, which are thus considered the northern limit of the Basin and Range province. The greatest offset is apparently recorded on the next zone to the south by the displacement of the eastern edges of the Sierra Nevada and Idaho batholiths. The two southern zones offset the Pleistocene to Holocene trend of the High Cascades by 10 to 20 km in a right-lateral sense. The Brothers fault zone, one of the northern zones, is regarded as of special interest because both ends of the fault are interpreted to be exposed at the surface. *Key words: structural geology, strike-slip faults, Basin and Range province.*

INTRODUCTION

Much discussion of the characteristics of faulting in the Basin and Range province of western North America has resulted in general agreement that these structures are the surface expression of overall east-west extension of the province during late Cenozoic time. The total amount of extension involved remains uncertain, but published estimates range from 50 to 200 km across the center of the province (Hamilton and Meyers, 1966; Stewart, 1971; Thompson and Burke, 1974). These figures suggest strain rates for the province between 10^{-16} and 10^{-15} sec^{-1}. For the Dixie Valley area, Thompson and Burke (1973) gave an average spreading rate over the past 15 m.y. of 0.4 cm/yr and a greater rate of about 1.0 cm/yr over the past 12,000 yr. These results are comparable to those calculated for the whole province. To date little attention has been focused on the manner in which this motion terminates to the north. The present paper offers one hypothesis on this question. A similar hypothesis for the southern termination of the province has been suggested by Davis and Burchfiel (1973).

The structural pattern of Oregon was studied on red band (band 5) and infrared band (band 7) satellite imagery recorded by the ERTS-1 (Earth Resources Technology Satellite). Figure 1 is a black-and-white mosaic of fall 1972 band 5 imagery illustrating the proposed hypothesis. On it a series of west-northwest–trending fault zones with proposed right-lateral strike-slip displacement separating areas of normal faulting are located. More extension is suggested for successively more southerly areas of normal faulting, culminating somewhere in central Nevada in the 50- to 200-km maximum cited above. The difference in net motion between zones is accommodated by strike-slip offset on the intervening faults. Thus, four identified fault zones cut through southeastern Oregon and form the transition between the main Basin and Range province of Nevada and the largely unfaulted Columbia River Plateau of north-central Oregon and southeastern Washington.

STRIKE-SLIP FAULT ZONES

Four zones extending west-northwest across much of Oregon are suggested as strike-slip fault zones. Of these the Brothers fault zone has been named and briefly described (Walker, 1969; Higgins and Waters, 1967). Informal names proposed herein for the other zones are the Vale zone and Eugene-Denio zone, shown by Walker (1973), and the Mount McLoughlin zone, parts of which are described by Pease (1969). The four zones are nearly parallel, and all break rocks of Pliocene or younger age. If faulting began at the same time as Basin and Range faulting in general, it has continued for the past 15 to 17 m.y. (Noble, 1972; Christiansen and Lipman, 1972).

Brothers Fault Zone

The clearest relationships occur along the Brothers fault zone, which extends about 300 km along a N60°W trend across central Oregon. This zone has a distinct east end at the Steens fault, one of the largest normal faults in Oregon. East of the Steens fault, normal faults of the basin-and-range type extend farther north into the state until they are largely terminated against the Vale fault zone. West of the Steens fault, normal faults largely end against the Brothers fault zone. North of this zone, recent deformation has largely involved folding and faulting on east-west and northwest trends (Walker, 1973; Brown and Thayer, 1966). Thus, the area north of the Brothers fault zone may be considered nearly stable in an east-west direction, whereas the area south of it shows extension in this direction. Since the Steens fault extends across the end of the Brothers fault zone, this end of the system can be considered fixed during at least the most recent history of the system. The result of these considerations is that the area south of the system must move west with respect to that to the north (Fig. 2), producing a right-lateral strike-slip fault. The amount of offset should increase from east to west along the fault. Unfortunately, the western end of the fault occurs in very young rocks and is obscured by Holocene ash from Newberry Caldera, so that such effects are not revealed.

The details of the Brothers fault zone support the preceding interpretation. The zone is made up of a series of discontinuous en echelon fractures trending about N40°W that are seen on ERTS imagery, aerial photography, and in the field. Many of these are apparently short normal faults, 10 to 20 km long, with intervening minor horsts and grabens. Less abundant faults, about 5 km long, trend about N30°E. This pattern is the same as that of strike-slip shear zones on many scales. The detailed analysis of such structures by Tchalenko (1970) suggests that the en echelon fractures are Riedel shears and the shorter fractures are conjugate Riedel shears. The acute angle between the trend of the en echelon fractures (N40°W) and that of the overall shear zone (N60°W) indicates right-lateral motion. The throughgoing fractures (called P shears by Tchalenko), where most of the strike-slip motion occurs, are not present. P shears are the last to appear, suggesting that relatively little motion has occurred across the Brothers fault zone. Because

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the Brothers fault zone is in rocks almost all less than 6 m.y. old and the strain rate south of the zone is herein considered less than that for the central Basin and Range province, the total strain at the surface could be less than is needed for a P-shear system. The presence of a concentration of volcanic vents along the zone supports the notion that it is a relatively deep seated fundamental tectonic feature, in spite of relatively limited visible offset. These vents become younger from east to west (Walker, 1974). If volcanism is concurrent with motion, this suggests that motion on the zone has also migrated from east to west.

Vale Zone

As noted above, normal faults extend north through the Owyhee Uplands east of the Steens fault. This area of extension ends mainly at the Vale zone. The location of this zone is based on the consistent linear trend of Willow Creek and of portions of the Snake River in Idaho, on parallel lineaments in the mountains to the west, and on termination of abundant normal faults at these features. The zone trends about N50° to 55°W. Heat-flow data of Bowen and Fisher (1974, oral commun.) show a sharp drop across it. In Idaho, basin-and-range faulting extends farther to the north. Thus the Vale zone is relatively short. The amount of right-lateral motion involved in this zone is presumed to be quite small (a few kilometres?), since the area of extension is narrow. Similar motion may continue on the faults extending from Walla Walla across the southern Wallowa Mountains to the Snake River. First-motion results from an earthquake in the southern Wallowa Mountains (Couch and Whitsett, 1969) are consistent with right-lateral motion.

Eugene-Denio Zone

Another band of fractures extends across most of Oregon about 100 km southwest of the Brothers fault zone. East of the 121st meridian, much of this band has been mapped by Walker (1974). The overall zone trends N55° to 60°W, and individual fractures trend about N50°W. The individual fractures are not interconnected, and most are less than 10 km long. I find the en echelon pattern to be less clear than on the Brothers fault zone, but it has

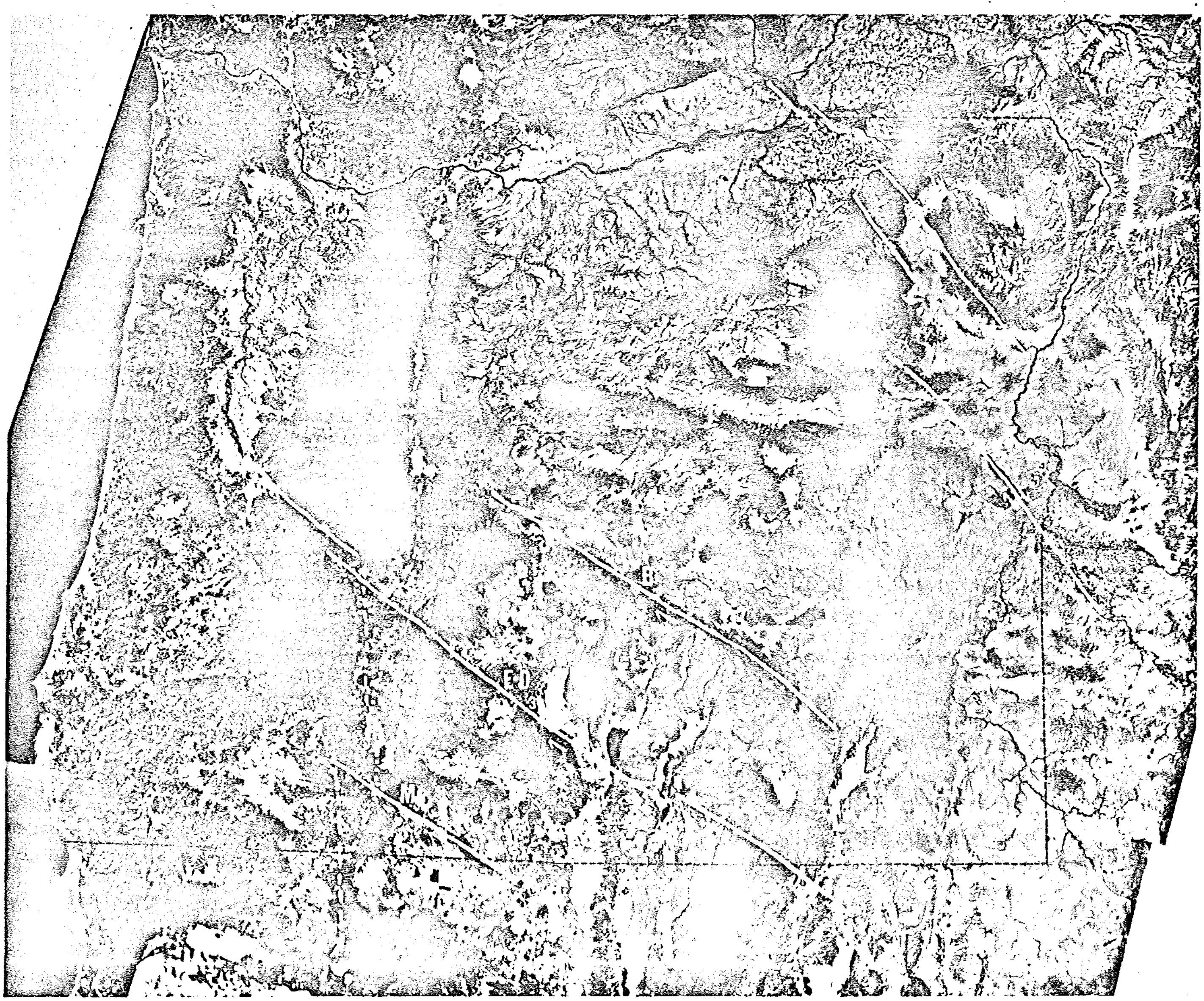

Figure 1. ERTS mosaic of Oregon showing strike-slip fault zones in relation to other features. V = Vale zone, B = Brothers fault zone, E-D = Eugene-Denio zone, and M = McLoughlin zone. Dashed line locates recent Cascade vents. Dotted line is boundary of Basin and Range province, not shown along B. Locations mentioned in text include (1) Green Ridge, (2) Walker Rim, (3) Winter Rim, (4) Abert Rim, and (5) Warner Rim.

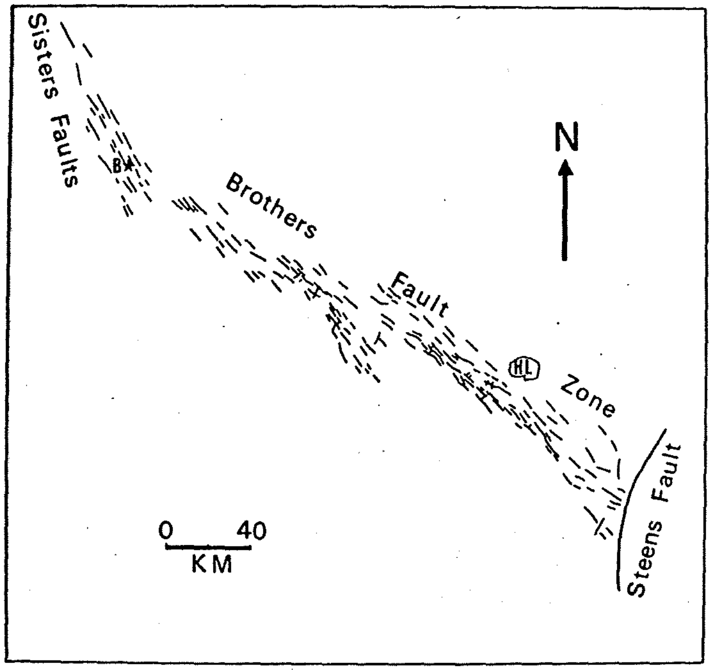

Figure 2. The Brothers fault zone as an en echelon set of fractures along a right-lateral shear zone (mapped on ERTS imagery). B = Bend, and HL = Harney Lake.

the same implication of right-lateral motion. The zone has been mapped through the Cascade Range as a series of lineaments. Many of these cross drainage divides without deflection, which indicates structural control. The High Cascade volcanic trend has about 10 to 20 km of right-lateral offset across the zone. At least two discontinuous offsets of the zone itself are present (Fig. 1).

This zone is associated with major changes in the basin-and-range pattern. The Summer Lake, Lake Abert, and Klamath Marsh basins and associated faults terminate against the zone. The Warner Lake basin is constricted and slightly offset by the zone. The Pueblo and Pine Forest Ranges and associated basins are offset along the zone. Similar disturbances of the basin-and-range pattern can be traced on ERTS imagery to the southeast across much of Nevada. A maximum estimate of the displacement along this zone may be derived from Taubeneck (1971), who estimated that as much as 80 km of offset in the alignment of the Idaho and Sierra Nevada batholiths has been accomplished by normal faulting, dike intrusion, and right-lateral faulting since the end of Oligocene time. The Eugene-Denio zone is located properly to produce a significant part of this motion.

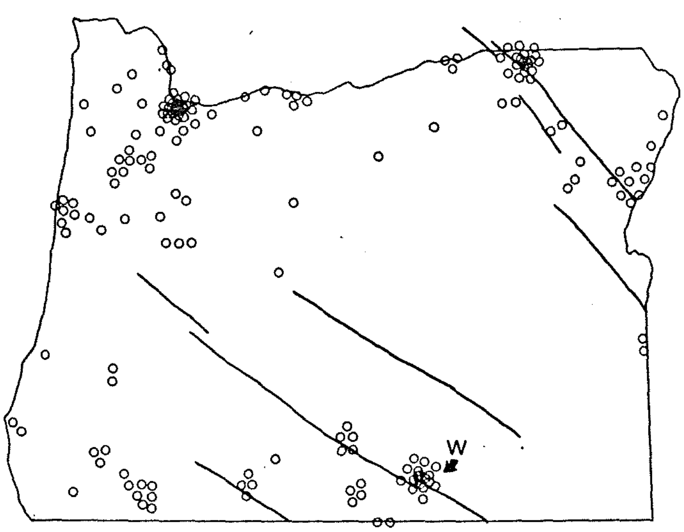

Figure 3. Earthquake epicenters in Oregon, 1841 to 1970 (after Couch and Lowell, 1971). W = Warner Valley swarm.

Mount McLoughlin Zone

The southwestern zone is similar to the Eugene-Denio zone in character. It includes many fractures interpreted as right-lateral fractures by Pease (1969). Individual fractures of the zone trend about N45°W, and the overall zone trends about N50° to 55°W, with the same implication as in each of the two zones to the north. At Mount McLoughlin this zone offsets the High Cascade trend about 15 to 20 km in a right-lateral sense. This zone does not obviously extend far into Nevada as does the Eugene-Denio zone.

BASIN-AND-RANGE FAULTING IN OREGON

The physiographic expression of the basin-and-range faults in Oregon changes dramatically across the Eugene-Denio zone (Fig. 1). North of the zone, many fault scarps, such as Walker Rim, Winter Rim, Abert Rim, and Warner Rim, are little modified by erosion. The volcanic uplands of the ranges probably retain nearly the surface formed by the most recent lava flows. The flat surfaces are clearly marked by numerous fractures of lesser offset. Thus the area north of the Eugene-Denio zone retains the features of a lava plain broken by block faulting but otherwise little modified. South of this zone, in most of the major ranges the original volcanic surfaces have been destroyed by erosion. Many fault-line scarps are present where weathering and erosion have produced scarp retreat. Only locally do unaffected faults occur. Locally, the contrast is related to changes in attitude and rock type across the zone that make erosion easier and more rapid to the south. The consistent contrast suggests, however, that major faults appeared earlier, perhaps by several million years, south of the zone than north of it. Although such an age contrast cannot be demonstrated from existing data, it is suitable to the hypothesis of this paper. Since significant strain must precede faulting, the greater total strain proposed for the area south of the Eugene-Denio zone would lead to earlier faulting than would occur north of the zone.

Studies of the seismicity of the Basin and Range province in Oregon are consistent with the concepts developed herein. Oregon has generally lower seismicity than the surrounding region, both in earthquake frequency and magnitude. Earthquake epicenters from 1841 to 1970 (Couch and Lowell, 1971) are plotted in Figure 3, along with the strike-slip fault zones suggested in this discussion. Within the Basin and Range province, most of the seismicity occurs along or south of the Eugene-Denio zone. The greatest concentration is the Warner Valley earthquake sequence, which coincides with one of the discontinuities in the zone. The lack of earthquakes north of this zone is interpreted to result from the lower strain rate. First-motion studies on the Warner Valley earthquake sequence (Couch and Johnson, 1968) indicate normal faulting on approximately north-south trends for eight shocks and either right-lateral faulting on west-northwest trends or left-lateral faulting on north-northeast trends for two shocks. The right-lateral result fits the trend of the Eugene-Denio zone. Because the sequence is located where both kinds of faults (normal and strike-slip) are postulated to occur, these first-motion results fit readily with the interpretation offered.

The most detailed study of the basin-and-range faulting in Oregon is that of Donath (1962) in the Summer Lake area, which clearly identified two major fault trends, one about N20° to 30°E and the other N30° to 40°W. Donath interpreted this rhombic pattern as due to north-south compression that produced a conjugate set of vertical strike-slip faults. More recent block faulting was considered to have produced the vertical offsets. Donath indicated that most of the exposed faults were vertical or nearly vertical in attitude. If this is correct, no extension occurs on the faults. This is in marked contrast to relations for the Basin and Range province as a whole, where similar rhombic patterns are produced simultaneously with extension (Thompson and Burke, 1974). The interlocking pattern of fault traces and irregular distribution of offsets were interpreted by Donath as evidence that all of the recent motion is dip slip. No offset markers or other evidence except the conjugate pattern could be found that demonstrated an earlier episode of strike-slip motion.

The pattern studied by Donath can be traced over the entire region on the ERTS-1 imagery. This imagery clearly shows that the same pattern is present throughout the area between the Brothers fault zone and the Eugene-Denio zone. The major basins and rim faults are mostly related to the northeast-trending fault set, Winter Rim being the most conspicuous exception. The northwest-trending set is largely expressed as somewhat smaller fractures that cut the uplifted blocks. This is also the set that curves continuously into the en echelon fracture sets of the strike-slip fault zones in a reverse S pattern (Fig. 4). As noted by Donath, neither set consistently offsets the other, and the pattern of fault traces that results is everywhere very angular and irregular so that the faults are interlocked. The motion on both sets is mainly dip slip. Thus, simultaneous motion is implied not only between the two basin-and-range fault sets, but also between these and the tear-fault zones. Evidence for right-lateral offset can be adduced along strike-slip fault zones, but none is present within the intervening blocks. Thus, it seems necessary to seek a new mechanical explanation for the rhombic pattern to replace Donath's hypothesis. Such a new explanation must produce the several sets of fractures simultaneously and with the same pattern of motion as currently exists.

HIGH CASCADE INTERACTION

The crest of the Oregon Cascades is a series of Pleistocene to Holocene volcanoes (mostly less than 1 m.y. old) and associated lava flows that occupy a downdropped block similar to many other volcano-tectonic depressions (Allen, 1965; Taylor, 1973; E. M. Taylor, 1974, personal commun.). The recent vents form north-trending linear features on the scale of the ERTS-1 imagery. Two of the strike-slip fault zones discussed above offset this trend in a right-lateral sense about 10 to 20 km. These offsets are the only known measure of the amount of offset on the strike-slip fault zones. They indicate that the total strain in each segment has decreased by about the same amount across each zone since the High Cascade trend was established. However, the Eugene-Denio zone is the one that extends a great distance into Nevada, suggesting that it is a particularly important feature in comparison to the less extensive Mount McLoughlin zone. Thus, it is equally reasonable to extrapolate a greater offset on this zone into the past.

Using typical values for the strain rate and total strain in the central Basin and Range province for the area south of the Mount McLoughlin zone, illustrative examples can be calculated to show the effect of the strike-slip fault zones under various assumptions (Table 1). In the first example, an arbitrary 20-km decrease in total extension across each zone and a 50-km minimum figure for the amount of basin-and-range extension have been used. In the second and third examples, the maximum offset has been placed on the Eugene-Denio zone with equal but lesser offsets on the Mount McLoughlin and Brothers fault zones. In the third example, the total extension has been increased to 100 km. Recalling that Thompson and Burke (1973) have shown that strain rates in the Basin and Range province are variable with time, it should be clear that these calculated examples serve largely to illustrate the step-down effect on strain rate here suggested for the area. The numerous assumptions inherent in obtaining the results forbid treating them as conclusions.

The Brothers fault zone appears to merge with the eastern faults of the High Cascade depression (Fig. 2). The apparent lack of offset across the High Cascades indicates that relatively little displacement has taken place along the Brothers fault zone. Such motion as has occurred in the past few million years must appear as extension of the High Cascades depression and, possibly, as spreading under the Deschutes basin. The interconnection is made by a gradual deflection of faulting to a N35°W trend from the N60°W trend of the zone. This deflection takes place on a series of small normal faults through the Deschutes basin (informally, the Sisters fault zone, Fig. 2). The individual fractures of this zone are parallel, rather than en echelon in pattern. The Sisters fault zone culminates in the Green Ridge fault, which trends about N25°W. At Green Ridge the faults are clearly the bounding structure of the volcano-tectonic depression of the Cascade crest (E. M. Taylor, 1974, oral commun.).

A similar interaction between basin-and-range features and the High Cascade depression occurs where the Klamath graben extends under Crater Lake. Here, normal faulting of the Basin and Range province merges directly with the volcano-tectonic depression.

Recalling the earlier discussion of the role of the Steens fault in addition to the reflections on the Sisters fault zone above, I interpret the Brothers fault zone as terminating at each end in a transition to normal faulting (Fig. 2). This implies that one has here the rather rare possibility of studying the actual ends of a large fault zone. At the Steens fault, a normal fault crosses and abruptly truncates the Brothers fault zone. Motion on the Steens fault has continued at least as long as on the Brothers fault zone. On the other hand, a

TABLE 1. EXAMPLES OF EFFECT OF TEAR-FAULT ZONES ON BASIN-AND-RANGE PARAMETERS

Location	Strain rate ($\times 10^{-16}$ sec^{-1})	Total extension (km)	Strain (%)
Example 1			
Between Eugene-Denio and Brothers fault zones	0.3	10	1.2
Between McLoughlin and Eugene-Denio zones	0.9	30	4
South of McLoughlin zone	0.3	50	6
Example 2			
Between Eugene-Denio and Brothers fault zones	0.3	10	1.2
Between McLoughlin and Eugene-Denio zones	1.1	40	5
South of McLoughlin zone	1.3	50	6
Example 3			
Between Eugene-Denio and Brothers fault zone	0.7	25	3
Between McLoughlin and Eugene-Denio zones	2.1	75	9
South of McLoughlin zone	2.6	100	12

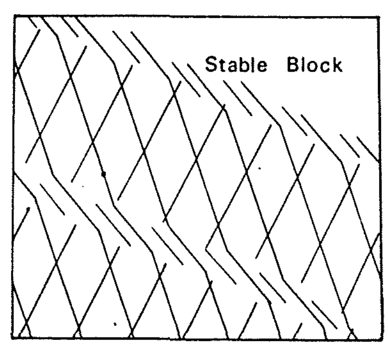

Figure 4. Idealized pattern of faulting for strike-slip faults and intervening extensional zones in southeastern Oregon.

gradual transition takes place to the Sisters fault zone, where motion is quite young and may have developed since the initial activity of the Brothers fault zone. In each case, however, the termination is exposed for study at the surface, unlike most major faults and fault zones, which disappear under more recent cover or are otherwise concealed.

DISCUSSION AND CONCLUSIONS

Large displacements due to right-lateral motion are also described along the Walker Lane and Death Valley–Furnace Creek zones of southwestern Nevada (Nielsen, 1965); however, most of this motion is reported (Stewart and others, 1968) to be of pre-Miocene age so that only a few kilometres are related to basin-and-range activity. The Oregon strike-slip fault zones, in contrast, are Miocene to Holocene features and are on about a 20° different trend. Thus these features are probably not directly related to one another.

The Basin and Range province in Oregon is hypothesized to terminate in a series of right-lateral strike-slip fault zones along which the total extension and extensional strain rates decrease progressively northward. Extension essentially ceases at the northern edge of the province along the Vale and Brothers fault zones. The rhombic pattern of normal faulting in the region results from the interaction of extension in blocks between the fault zones and the right-lateral strike-slip motion along the zones at the edges of the blocks. The net offsets on individual strike-slip fault zones are estimated to be in the range of a few tens of kilometres.

A similar interpretation of the tectonic role of the Garlock fault has been made by Davis and Burchfiel (1973). They suggested that the southern termination of basin-and-range extension occurs by left-lateral strike-slip motion along the Garlock fault. Combined with the present work, this provides an overall interpretation of the Basin and Range province as an area bulging westward between terminal strike-slip fault systems to the north and south. The strike-slip faults function in a manner exactly analogous to tear faults bounding a farther moved section of a thrust block. The trends of the Garlock fault and the Oregon strike-slip fault zones are not parallel but diverge toward the west. They may define the area of mantle diapiric bulge suggested by Scholz and others (1971) to be the origin of basin-and-range extension that reflects stress relief associated with the change of the western edge of the American plate from a convergent to a transform boundary.

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