LARGE SCALE TEAR FAULTING AT THE NORTHERN TERMINATION OF THE BASIN AND RANGE PROVINCE IN OREGON

Robert D. Lawrence

Abstract

The pattern of faulting in southeast Oregon is interpreted in terms of four major zones of right lateral tear faulting which separate blocks broken by normal faulting. The total amount of east-west extension is considered to decrease in the block north of each tear fault zone. The right lateral offset results from the decrease in extension. Extension essentially dies out across the Vale and Brothers Fault Zones which are thus considered the northern limit of the Basin and Range Province. The greatest offset is apparently recorded on the Eugene-Denio Zone by the displacement of the eastern edges of the Sierra Nevada and Idaho Batholiths. The Eugene-Denio and Mt. McLoughlin Zones offset the Pleistocene to Recent trend of the High Cascades by 10 to 20 km in a right lateral sense. The Brothers Fault Zone is regarded as of especial interest because both ends of the fault are interpreted to be exposed at the surface.

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 with published estimates ranging from 50 km to 200 km across the center of the province (Hamilton and Meyers, 1966; Stewart, 1971; Thompson and Burke, 1974). Using these figures strain rates for the province range between 10^{-16} and 10^{-15}/sec. For the Dixie Valley area Thompson and Burke (1973) give an average spreading rate over the last 15 million years of 0.4 cm/yr and a greater rate of about 1.0 cm/yr over the last 12,000 years. 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.

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. It shows a series of west-northwest trending tear fault zones with postulated right-lateral strike slip displacement separating areas of normal faulting. More extension is suggested for successively more southerly areas of normal faulting, culminating in the 50-200 km maximum cited above somewhere in central Nevada. The difference in net motion between zones is accomodated by offset on the intervening tear faults. Thus four identified tear fault zones cut through southeast Oregon and form the transition between the main Basin and Range extension province of Nevada and the largely unfaulted Columbia River Plateau of north-central Oregon and southeast Washington.

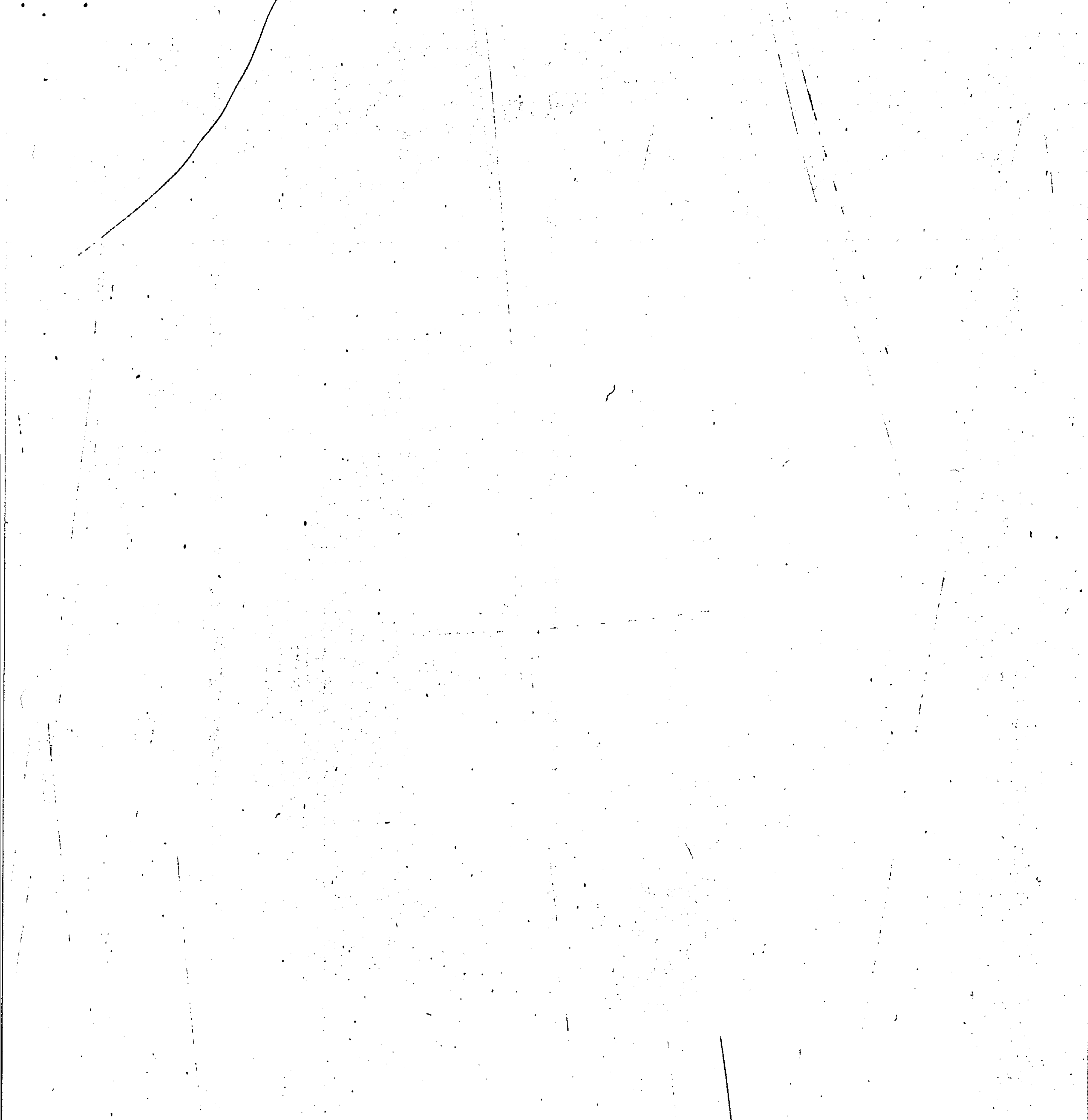

Figure 1. ERTS mosaic of Oregon showing tear fault zones in relation to other features. V = Vale Zone, B = Brothers Fault Zone, E-D = Eugene-Denio Zone, and M = McLoughlin Zone. Dashed line locates recent Cascade vents. Dotted line is boundary of Basin and Range Province.

The Tear Fault Zones

Four zones extending west-northwest across much of Oregon are suggested as tear fault zones. Of these the Brothers Fault Zone has been named and briefly described (Walker, 1969). Informal names proposed herein for the other zones are the Vale Zone, the Eugene-Denio Zone, and the Mt. McLoughlin Zone. Portions of the Eugene-Denio Zone are shown by Walker (1973) and parts of the Mt. McLoughlin Zone are described by Pease (1969). The four zones are nearly parallel, and all break rocks of Pliocene or younger age. During this study no evidence on the time of initiation of faulting was obtained, but if it began at the same time as Basin and Range faulting in general, it has continued for the last 15-17 million years (Noble, 1972; Christiansen and Lipman, 1972). The main concern of this study, however, is the present tectonic pattern.

The 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 faulting of the Basin and Range type extends further north into the state until it is largely terminated against the Vale Fault Zone. West of the Steens Fault, normal faulting largely ends 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, while the area south of it shows extension in this direction. As 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 (figure 2), producing a right-lateral tear 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 recent ash from Newberry Caldera so that such effects are not recorded.

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. Many of these are apparently short normal faults, 10-20 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

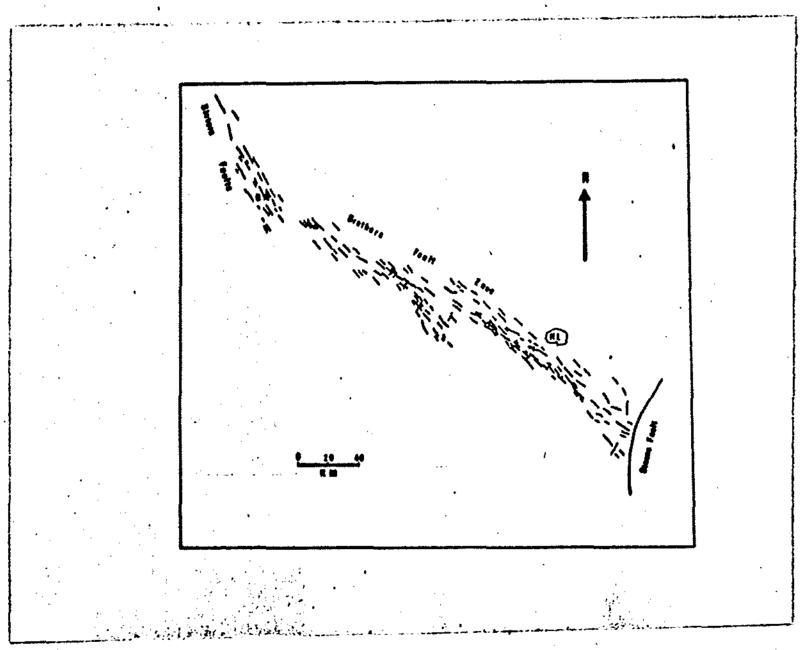

Figure 2. The Brothers Fault Zone as an en echelon set of fractures along a right lateral shear zone (mapped on ERTS imagery). B = Bend and HL = Harney Lake.

relatively little motion has occurred across the Brothers Fault Zone. As the Brothers Fault Zone is in rocks almost all less than 6 million years 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.

The Vale Zone. As noted above, normal faulting extends north through the Owyhee Uplands east of the Steens Mountain 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 faulting at these features. The zone trends about N50-55°W. Heat flow data of Bowen and Fisher (personal communication, 1974) 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 as the area of extension is narrow. Similar motion may continue on the faulting extending from Walla Walla across the southern Wallowa Mountains to the Snake River. First motion results from an earthquake in the southern Wallowas (Couch and Whitsett, 1969) are consistent with right-lateral motion.

The Eugene-Denio Zone. About 100 km southwest of the Brothers Fault Zone another band of fractures extends across most of Oregon. East of the 121st meridian much of this band has been mapped by Walker (1974). The overall zone trends N55-60°W and individual fractures trend about N50°W. The individual fractures are not interconnected and most are less than 10 km long. The en echelon pattern is less clear than on the Brothers Fault Zone, but has 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 indicating structural control. The High Cascade volcanic trend has about 10-20 km of right lateral offset across the zone. At least two discontinuous offsets of the zone itself are present (figure 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. An maximum estimate of the displacement along this zone may be derived from Taubeneck (1971) who estimates 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 the Oligocene. The Eugene-Denio Zone is located properly to produce a significant part of this motion.

The Mt. 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 N50-55°W, with the same implication as in each of the two zones to the north. At Mt. McLoughlin this zone offsets the High Cascade trend about 15-20 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 Faulting in Oregon changes dramatically across the Eugene-Denio Zone (figure 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 which make erosion easier and more rapid to the south. The consistent contrast suggests, however that major faults appeared somewhat earlier, perhaps several million years, south of the zone than north of it. While 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 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 1841-1970 (Couch and Lowell, 1971) are plotted on figure 3 along with the tear 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 as a result of 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 8 shocks and either right lateral faulting on west-northwest trends or left lateral faulting on north-northeast trends for 2 shocks. The right lateral result fits the trend of the Eugene-Denio Zone. As the sequence is located

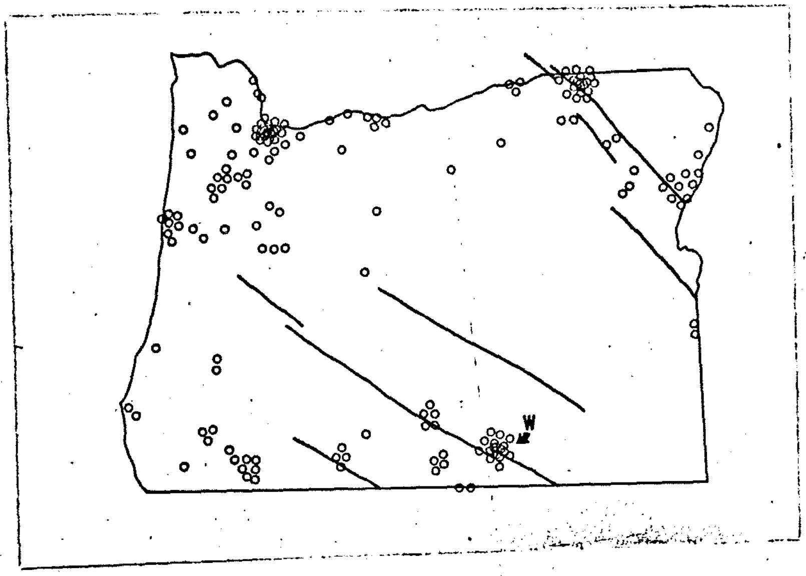

Figure 3. Earthquake epicenters in Oregon, 1841-1970 (after Couch and Lowell, 1971). W = Warner Valley swarm.

where both kinds of fault (normal and tear) 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: about N20-30°E and N30-40°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. He 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 for which there is evidence is dip slip. No offset markers or other evidence except the conjugate pattern could be found which 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 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 tear fault zones in a reversed "S" pattern (figure 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, 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 Interactions

The crest of the Oregon Cascades is a series of Pleistocene to Recent volcanoes (mostly less than 1 million years old) and associated lava flows that occupy a down dropped block similar to many other volcano-tectonic depressions (Allen, 1965; Taylor, 1973, and personal communication). Within these features the recent vents form north-south linear features on the scale of the ERTS-1 imagery. Two of the tear 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 tear fault zones. It indicates that the total strain in each segment has decreased by about the same amount across each zone since the

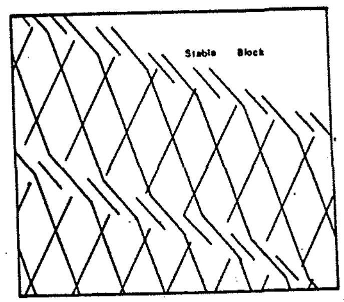

Figure 4. Idealized pattern of faulting for tear faults with intervening extensional zones in southeastern Oregon.

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 Mt. 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 Mt. McLoughlin Zone, illustrative examples can be calculated to show the effect of the tear 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, lesser offsets on the Mt. 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 Basin and Range strain rates are variable with time, it should be clear that these calculated examples serve largely to illustrate the step-down effect on strain rate that this writer suggests 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 (figure 2). The apparent

Table 1. Examples of effect of tear fault zones on Basin and Range parameters.

	Location	$\dot{\varepsilon} \times 10^{-16}$/sec	Total extension	% strain
Example 1	Between Eugene-Denio and Brothers Fault Zones	0.3	10 km	1.2
	Between McLoughlin and Eugene-Denio Zones	0.9	30 km	4
	South of McLoughlin Zone	.3	50 km	6
Example 2	Between Eugene-Denio and Brothers Fault Zones	0.3	10 km	1.2
	Between McLoughlin and Eugene-Denio Zones	1.1	40 km	5
	South of McLoughlin Zone	1.3	50 km	6
Example 3	Between Eugene-Denio and Brothers Fault Zone	0.7	25 km	3
	Between McLoughlin and Eugene-Denio Zones	2.1	75 km	9
	South of McLoughlin Zone	2.6	100 km	12

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 last 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). 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 faulting is clearly the bounding structure of the volcano-tectonic depression of the Cascade crest (Taylor, personal communication).

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 depresssion.

Recalling the earlier discussion of the role of the Steens Fault in addition to the reflections on the Sisters Fault Zone above, the writer interprets the Brothers Fault Zone as terminating at each end in a transition to normal faulting. If correct, this implies that one has here the rather rare possibility of studying the actual ends of a major fault zone. At the Steens Fault, normal faulting 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 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; Stewart, Albers, and Poole, 1968). However, most of this motion is of pre-Miocene age and only a few tens of kilometers are related to Basin and Range activity. The Oregon tear fault zones, in contrast, are Miocene to Recent 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 believed to terminate in a series of right lateral tear 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. The net offsets on individual tear fault zones are estimated to be in the range of a few tens of kilometers, with about 80 km as a maximum.

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