Extensional Faulting in the Great Basin: Kinematics and Possible Changes with Depth

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Abstract

The Great Basin (northern Basin-Range Province in the western U.S.) is a 5×10^5 km^2 region of extensional failure which has been active for >15 m.y. The region seems to be undergoing generally westward spreading at ~ 10^{-15} s^{-1} but with divergence along its western marginal zone.

Current appreciation of the architecture and kinematics of fault zones in the Great Basin is gained from exposures in the upper 2 km provided by fault block mountains and from seismicity. The region seems to be underlain by three rheologic layers: a) a brittle upper layer, ~ 5 km thick, composed of blocks in a shattered mosaic. The blocks move passively with reasonably co-ordinated displacements and are probably driven by motions in subjacent layers; displacement occurs on well defined but irregularly configured fault surfaces which bound the blocks. Most major faults strike at high angles to the local extension direction except in regions where strong basement anisotropy controls fault orientation. b) an intermediate layer, 5 to 15–20 km deep, which contains most of the seismic slip; it is capable of accumulating sufficient strain for large (M 7–8) earthquakes on steep fault zones that strike at high angles to the regional extension; slip in such zones may become more distributed with depth but within a narrowly confined volume; where slip is at low angles to regional extension in layer b, large earthquakes seem not to occur and shear surfaces appear to be widely distributed: c) the region below layer b is apparently ductile. Spatial variations in rates of seismicity in the Great Basin are related to regional topographic slope. Corresponding topographic shear stress in layer b is as great as 25 bar.

Great Basin: Regional Properties

The Great Basin (Fig. 1) is characterized by widespread normal faulting that has occurred in later Cenozoic time and continues today as indicated by seismicity, Holocene and Pleistocene scarps, and impressive fault block relief. High mean elevation (1700 m) and heat flow (ca 2 hfu; Lachenbruch and Sass, 1979) are also important characteristics. Analysis of the free air gravity field by Cogbill (1979) indicates there is probably a close approach to uniformity of mass/area at wavelengths exceeding 100 km.

It appears that ancient sialic crust, 25–30 km thick, underlies the Great Basin east and south of a curved pre-Tertiary suture (Fig. 1) and that accreted microplates of noncontinental origin underlie the territory northwest of that boundary. Upper mantle velocities below the Great Basin are subnormal ($P_n \sim 7.4$ to 7.9 km sec^{-1}), and attenuation is strong, apparently to great depths (Archambeau and others, 1969). Models based on refraction data imply the existence of crustal velocity reversals in sialic regions of the Great Basin (Prohdehl, 1970; Braile and others, 1976).

Within the Great Basin, there are evident zonations of properties. Earthquake frequency and magnitude ($M<8$) are greatest in the marginal zones (except for the northern) and are maximum in the western zone (Fig. 1). A belt of regionally minimum elevation (1000 m below max.) and of locally elevated heat flow also follows the western margin and contains the seismic maxima. Patterns of traces of major faults also indicate zonation: a province-crossing band of NW-striking faults called the Walker Lane (Fig. 1) separates a region of NNW and ENE-striking faults on its SW side from the rest of the Great Basin to the NE where N to NE strikes predominate.

Volcanism has occurred widely over the Great Basin in the last 40 m.y. but in the last 5–10 m.y., extrusion has been confined to the margins of the province. Various space-time patterns of volcanism have been proposed, but the latest assessment seems to show contemporaneous onset of extensive volcanism across the entire region (Christianson and McKee, 1979). It is widely held that the onset of widespread basin-range faulting was at 15–20 myBP. Some studies, however, imply that faulting that is related to modern basin-range systems began significantly before 20 myBP (e.g., Speed and Cogbill, 1979).

The properties described lead to the obvious conclusion that the lithosphere and the zone of brittle failure in the Great Basin are markedly thinner than in typical cratonal terranes (e.g. Scholz and others, 1971; Stewart, 1971; Thompson and Burke, 1974).

Surface heat flows reduced for lithospheric heat generation (heat production-depth product ~ 0.5 hfu, Lachenbruch and Sass, 1979) can be reasonably taken as 2 and 1.5 hfu in the western and central zones, respectively. Corresponding steady state conductive temperature gradients would be about 33 and 25 °C/km. Thus, crustal low velocity zones in the sialic central and eastern regions of the Great Basin can be related to incipient melting, and there, the base of the lithosphere is probably between 20 and 30 km depth. It is uncertain whether the lithosphere thickens or thins toward the NW Great Basin: although the isotherms shallow in that direction, the lithosphere in the NW region may have a substantially higher temperature solidus than that where sialic crust prevails.

Faults: Surface and Near-surface

The structural depth to which normal faults of the Great Basin may be observed at the surface and in mines is generally ≤ 2 km. Surface observations indicate that the outer crust of the Great Basin is a mosaic of blocks which are internally coherent and which lack evident late Cenozoic strain. The faults which bound the blocks seem to have taken up the bulk of the relative motions. These major faults are commonly single surfaces, or they may be a zone of anastomosing strands rarely exceeding 100 m wide in bedrock; in alluvium, there is generally a wider zone of ground breakage. Figure 1 shows traces of most of the major block-bounding faults. Although the map pattern implies general linearity of trace, basin-range faults are characteristically crooked in detail; the strike of continuous fault surfaces commonly varies by as much as 90° over lengths of a few kilometers. Dips vary generally between 50 and 90°, but are demonstrably at lower angle at a few places. Trace lengths of apparently continuous faults as great as 150 Ian are known, but such values are probably exceptional. Zones of surface faulting associated with large historic earthquakes ($6.8 \leq M \leq 7.2$) are between 35 and 50 km long and have slip lengths up to 3 m (Wallace, 1977).

The sense of slip (right or left-oblique) varies with strike and position of the fault in the province, as discussed later. Throws are commonly as great as 3 km, exceptionally 5 km. Finite net slip of major faults cannot generally be measured directly but can be estimated to be <7 Ian.

The nature of the ends of faults is generally obscure because they are so commonly suballuvial. It seems probable, however, that most intersect other faults rather than grade into a strained continuum. There is no implication of time sequence of fault growth by such intersections. Demonstrable offsets of one fault by another are rare in the Great Basin. Where the main faults have similar average strikes and significant throw, the enclosed blocks are elongate and form the striking linear topographic patterns for which the province is well known ("worms marching toward Mexico"). The average spacing of such faults is 15-20 km. Where average fault strikes are more diverse, trace lengths are shorter and the topography less patterned. The irregular blocks contained in such arrays seem to have mean horizontal dimensions <15 km.

Exposures of movement surfaces of main basin-range faults are rare. One evident reason is the rapid erosion from range fronts and submergence below alluvium in basins. Moreover; motion on many faults within ranges have local downhill components and may not be directly coordinated with basin-range tectonics. Specifically, fault's within packets of Cenozoic rocks may be related to adjustments during décollement on the regional unconformity between Cenozoic and older rocks.

Although the Great Basin is active as a whole and basin-range relief is not significantly different across the province, spatial variations in sharpness, length, and density of Quaternary fault scarps (chiefly intra-alluvial) and in seismicity indicate zonation in rate of faulting (Slemmons, 1967; Wallace, 1977; Ryall, 1977). In the central Great Basin, scarps have short trace length and more eroded profiles compared to those in the western and eastern regions. Judging from scarp characteristics created by historic earthquakes in the western Great Basin, Wallace (1977) believed that slip due to major ($M \geq 7$) earthquakes is undetectable in the Quaternary record of the central zone. In contrast, scarps in the western and eastern zones imply that 5 to 50 such events per 1000 km^2 have occurred in the last million years. The zonation in Quaternary paleoseismicity seems to be reflected in the historic seismic flux (Ryall, 1977) which compares time integrated seismic energy among spatial domains.

The western zone contains a narrow belt (eastern branch of Y pattern, Fig. 1) in which large historic earthquakes and scarps (Wallace, 1978) indicate particularly high seismic outflux over at least the last 10^5 yr (perhaps as much as 300 M7-8 quakes/1000 km^2). Within this belt, however, Wallace (1978) has shown that there is little evident spatial pattern to the sequence of major faulting events. There has not been a systematic migration of displacements. Repeated movements seem to have occurred on some alluvial scarp clusters whereas adjacent tracts within the belt have been largely dormant. Even within a set of related scarps, some record many offsets whereas others show only one or so.

Some domains in the western seismic belt have negligible modern seismicity and few alluvial scarps but have high steep bedrock mountain fronts which imply large uplift rates. For example, the imposing White Mountains front (W, Fig. 1) can be estimated to have risen at roughly 0.8 m/1000 yr over the last 2 m.y. But, there have been no associated historic large earthquakes, and alluvial scarps are infrequent and probably 2000 or more years old. The characteristics of such domains may suggest that the western seismic belt is subjected to infrequent earthquakes whose magnitude and throw are decidedly greater than what has been seen in the historic record. Alternatively, one may interpret that aseismic displacements provide much of the observed throw in these domains. It would then follow that steady or episodic creep could occur elsewhere in the Great: Basin.

Explanations of regional differences in Quaternary faulting include: 1) the locus of maximum rate of slip and seismicity in the Great Basin is transient: and has criss-crossed the province leaving a spoor of rejuvenated fault block mountains whose steepness and average relief persist for millions of years: 2) seismic faulting throughout Great Basin is everywhere sufficient to account for basin-range relief but increased proportions of lateral (extension and strike slip) to vertical motions account for the greater seismic outflux in the western and eastern zones (outflux taken as steady); and 3) aseismic slip may contribute more pervasively to displacements in the central zone.

Fault rock: Fault rock can be studied adequately only in mines, and there, overprints of hydrothermal effects are commonplace. A few general observations, however, are possible. Fault planes of more than incipient offset typically have slikensided polished faces in soft and hard rocks. The spectrum of slikensides sizes (profile and length) varies on different faults, but there is not an evident relation of size vs rock properties or total slip (poorly known in general). In soft rocks (e.g., mudstone) fault rock consists of ductile gouge whose width varies greatly along strike. Undulous masses of gouge consist of composite packets joined by folded shear surfaces with deformed striations. There is generally no simple rotation history that can account for the geometry of the composites. The gouge undulations may be continually accreting as quasi-rigid walls of the fault zone slip by them and undergoing simultaneous rotational strain. Some gouge undulations have been cut through by plane faults. Faults in harder rock (e.g., greenstone) occupy narrow zones that grade precipitously from a polished face through unfoliated cataclasite of increasing mean diameter of fault clasts to fractured rock. Not enough is known of displacement magnitudes on the few individual faults that have been studied to pose any relationship between fault rock and fault kinematics. The widest gouge zone I have seen is 100 m (normal to a vertical fault); fault slip magnitude is about 2 km, left oblique slip with strike slip/dipslip = 2.5. At most places, widths of fault rocks are a tenth or hundredth of this.

The depth of formation of fault rocks described above is almost certainly less than 2 km and mostly less than 500 m. Motions of adjacent walls seem to have occurred largely by slip on a narrow surface. There is no evidence that strain or distributed slip in the walls has taken up significant motion outside the narrow zones of evident cataclasis.

It is worth noting that Proffett (1977) found that clay gouge is more brittle and occurs in narrower zones at deeper levels (4 km?) of basin-range faults at Yerington, Nevada.

Mina Region: The 2500 km^2 Mina region lies in the western marginal zone of the Great Basin astride the belt of maximum seismicity (Figs. 1,2). The region includes faults of generally anomalous orientation: in the western domain, major faults (faults with long trace length and greatest apparent displacement) chiefly strike ENE whereas in the eastern domain, they strike NNW and lie in the so-called Walker Lane. In the broader view, the ENE faults of the Mina region seem to form the intermediate leg of a gigantic Z pattern of fault strikes. Data on surface faults of the Mina region in conjunction with seismic parameters provide clues to the kinematics and architecture of fault zones with depth in the western Great Basin.

Detailed study (Speed and Cogbill, 1979) of one of the E-striking fault zones in the western domain of the Mina region indicates activity from 25 myBP or before into the Quaternary. The sense of slip is left-oblique normal, and the displacement direction has not changed significantly with time; the rate of slip, however, has certainly varied over the history of motion. Elsewhere in the western domain, the main faults (long trace length, largest finite slip) have similar attitudes and sense of slip; the ratio of strike slip to dip slip varies from 2 to 6, as determined chiefly by incremental markers. The main E-striking faults are spaced about 5 km apart over the region of recognized occurrence (30-35 km NS). Estimates of net slip magnitude between 1.5 and 4 km can be made for three of these faults. The Excelsior Mt. fault (E, Fig. 2) broke ground with left-oblique normal slip during an earthquake (M = 6.3) in 1934 (Callahan and Gianella, 1935), demonstrating modern activity on this fault set.

In the eastern domain of the Mina region, the main faults (NNW-striking) are right-oblique normal where sense of slip has been determined. Net slip magnitudes are poorly known, but probably are a few kilometers or less. Spacing of main faults is about 1 per 5 km over 25-30 km normal to strike. The 1932

Cedar Mts. earthquake (M = 7.2) occurred on one or more suballuvial faults of this set and caused ground breakage with right-oblique displacement over a zone 60 km long, parallel to strike and 6-15 across strike (Gianella and Callaghan, 1934). The scarp at the base of the Pilot Mts. frontal fault (P, Fig. 2) of this set is probably Holocene. The time span over which the NNW-striking faults have been active has not been determined from direct evidence.

At intersections of faults of the two main sets in the Mina region, displacements appear to be coordinated. That is, incremental slip markers are largely parallel on the nearly orthogonal fault faces and are colinear with the fault intersection. Offsets of faults of one set by another have not been detected. Thus, the area of gradation between domains of different predominant fault strike (mostly suballuvial) probably has unusually doglegged faults. The general compatibility of displacements and the lack of evident sequencing of motions between faults of the two domains permit the history of faulting in the eastern and western domains to have been similarly long.

Figure 3a shows composite orientations of fault planes and striae *on* plane bedrock fault faces throughout the Mina region. Poles to planes represent a single fault strand of about ±5° strike, regardless of length; striae do not occur on all planes represented. It is evident that fault planes dip in all directions except, apparently, to the east. Striae, however, lie in a girdle of W to N80W strike. Some striae, however, lie off the girdle; many of these are oriented down the dip of EW striking fault planes which face surface declivities and may have topographically induced slip. The striae data imply that the ratio of horizontal/vertical components of slip is directionally variable. Assume that finite and infinitesimal slip on each fault have been parallel and that the average throw has been constant per azimuth (θ). (The latter assumption is supported by the lack of distinct topographic grain to the region.) Given η slip directions of plunge ϕ,

$$\bar{\phi}(\theta) = \Sigma\, \phi(\theta)/\eta \quad \text{and}$$

$$\bar{r}(\theta) = \bar{T}\cot\bar{\phi}(\theta)$$

where T is the throw and r is the horizontal component. Maximum r trends between EW and N80W and is apparently the direction of greatest elongation (assuming shortening is vertical). The orthogonal elongation is about NS and is about 0.1 r_{max}. Under the assumed conditions, late Cenozoic strain in the Mina region due to faulting has horizontal flattening with a ratio $X/Y \approx 10$ and a maximum westerly rate of spreading. For geometric comparison, perfect uniaxial extension in the vertical plane would yield coplanar striae, and individual striae would lie along the intersections of the containing fault plane and the extension plane.

The directionality of extension by faulting in the Mina region implies significant compatibility in the relative motions of component blocks. The implication is strengthened by the general parallelism of slip directions and intersections of planar segments of zigzag faults. The distribution and orientations of faults relative to the extension direction in the Mina region, however, do not seem to relate to theoretical patterns of multiple fractures which cause homogeneous strain by compatible progressive slip (e.g., Taylor, 1938; Reches, 1978). The assumptions of isotropy in shear strength and coaxial strain in such models may invalidate the comparison. Instead, the impression is gained from Figure 2 that block boundaries evolved from an initial array of steep cracks with almost random strikes and that fractures of only ENE and NNW strikes evolved into major faults. Figure 3c shows a plane strain model of compatible slips between these two fault sets.

The basis for kinematic selection of the ENE set by strength anisotropy seems clear. The strongly layered bedrock of the Mina region predominately strikes ENE and dips steeply, and such structure is likely to extend to considerable depth (see later). The selection of the NNW-striking faults, however, is less evident. They may have evolved from early through-going faults related to the Walker Lane, which may be a failed intraplate shear zone related to early motions of the San Andreas system. On the other hand, the NNW faults may simply have been selected for compatible motions with the strength-controlled ENE set.

Regional Extension

Assuming that basin-range faults dip at 60° to the base of the faulted layer, one can estimate a minimum of about 100 km total extension in an EW direction across the Great Basin (Stewart, 1971; Thompson and Burke, 1974). This direction is approximately normal to average fault strike at 40°N (Fig. 1). The displacement corresponds to a longitudinal strain of about 0.125 and a steady strain rate of $10^{-15.6}$ s^{-1} over 17 m.y.

In fact, the actual directions of extension vs. position in the Great Basin are known sparingly, and current appreciation (Fig. 1) implies they vary widely but systematically in the western marginal zone. The measures used for such trends are finite displacement of linear markers (rare) and incremental slip markers on plane bedrock faults (striae). Each double arrow in Figure 1 is the mean azimuthal distribution whose la varies from about 5 to 20. The data used for extension directions vary from place to place: at M and Y, they include many faults and commonly, markers at several positions on each fault; at the other locations, markers were measured on a single fault system over trace lengths between 5 and 40 km. The ages of the incremental markers are generally unknown (most are on bedrock faults with respect to alluvium). Net slip trends from nodal planes of composite focal mechanism diagrams (plane closest to local orientation of major faults) are shown by single arrow in Figure 1. There is good correspondence between extension directions indicated by fault markers and seismic data, except in the northernmost part of the belt.

There is almost no information available on trends of fault slips in the central and eastern Great Basin. Striae on the Wasatch fault near Salt Lake City indicate EW extension. In the absence of direct measures, however, slip directions may be suggested by intersections of plane segments of zigzag faults. In the western Great Basin where fault face striae have been studied, intersections of plane segments of zigzag faults generally lie in the same orientation range as the striae. This implies that progressive slip on a given zigzag fault is rectilinear and volume conservative. Assuming this to be true on dogleg fault surfaces throughout the Great Basin, map data on fault attitudes suggest EW extension is probable in the central and eastern parts of the province.

The extension directions along the western margin of the Great Basin vary from WSW at the southern end (left slip on the transcurrent Garlock fault) to NW at the northern. It is uncertain whether extension directions vary smoothly through the Walker Lane or jump across it by 30° or more. If the directional changes are gradational, the general pattern of extension suggests a divergent westerly outflow in the western marginal zone of the Great Basin.

Figure 1 shows that except in the Mina and Cortez regions, average strikes of major faults in the western marginal zone are at high angles to local extension directions. There is, however, a systematic departure from perpendicularity with the acute angle to the north, and the sense of slip on such faults is therefore right-oblique.

The question arises whether trends of incremental slip (striae or focal mechanism net slip) record past extension directions or whether such directions have changed with time due either to a) rotational strain during progressive deformation of the Great Basin and(or) b) major changes in the motions at the boundaries of the Great Basin. For example, the Great Basin might be regarded as a remarkably wide zone of dextral NW-trending simple shear in which part of the relative motion of the Pacific and American plates is taken up. To account for a simple elongation of 0.125, the shear strain required across the region would be only about 0.24. Thus, the rotation of the direction of finite elongation with respect to that of incremental elongation would, under such circumstances, be only 3-4°. Such small angular differences could not be detected with the imprecise measures at hand. It is unlikely that rotation through progressive deformation is significant unless shear has been concentrated in narrow belts that include areas where extension directions have been measured.

With regard to changes in boundary motions, evidence at Yerington (Y, Fig. 1; Proffett, 1977) and Mina (M, Fig. 1; Speed and Cogbill, 1979) suggests that extension directions have been reasonably uniform over more than 15 m.y. of faulting in these regions. Zoback and Thompson (1978) and Zoback (1978). however, proposed that an abrupt change in extension direction occurred in late Cenozoic time in the northern part of the western Great Basin due to a change in plate motions outside the region. If they are correct, the present pattern of extension as a whole may apply for only the last few million years.

Faults vs. Depth

An unresolved problem of fundamental importance to an understanding of basin-range faulting is whether or not the architecture and kinematics of faulting change with depth below the upper few kilometers. Two questions can be set forth: 1) does the zigzag planarity of faults in the upper few km continue to depth, or is this simply the surface expression of listric faults which decrease dip with depth to the limit of horizontality; and 2) is displacement spaced on discrete zones at depth as at the surface, or does the displacement become more distributed or less distributed with depth?

Listric faulting has certainly occurred locally in the Basin-Range Province where there are nested shallow-dipping normal faults whose hanging walls -contain steeply-tilted Cenozoic and older layered rocks (fault ∧ bed ≈ 90°)(Lake Mead, Anderson, 1971: Death Valley, D, Fig. 1; Wright and Troxel. 1973; Yerington, Y, Fig. 1, Proffett, 1977). Fault inclination is generally less with depth of expasure. The near-horizontal detachment zones into which the listric faults presumably discharge are not exposed. At Lake Mead and Death Valley, such zones are estimated by projection of surface geometry to be within the crystalline basement at depths of a few kilometers below surface. At Yerington, the depth was questionably estimated at 16 km. Listric faulting at all three sites was accompanied by local magmatism. The listric faulted terrane at Lake Mead is surely a thin-skinned feature (Anderson, 1971). It is not clear at the other two places whether the basin-range structure is entirely a product of listric faulting above a décollement or whether the décollement is early and broken by younger steep normal faults (although authors assert the first case).

Evidence at other places in the Great Basin, however, seems to indicate that curvature is not significant on major basin-range faults, as advocated by Stewart (1971) and Thompson and Burke (1974). Dips of Cenozoic layering are generally shallow (<30°), indicating minor rotation due to basin-range faulting, Distributions of hypocenters in aftershock zones and of microearthquakes in the seismic belt of the western Great Basin (e.g., Smith and others, 1972) provide no evidence for listric faults.

The second question, whether displacement is concentrated on discrete fault surfaces at depth as in the near-surface, is considered below in the light of seismic parameters.

Seismic parameters: The main seismic belt of the western Great Basin is the eastern branch of the Y-pattern in Figure 1. Maximum epicenter density in this belt is defined chiefly by aftershock clusters from large historic earthquakes ($M \geq 6.8$); the clusters are well aligned astride or just adjacent to zones of ground breakage on the faults whose strikes are northerly. Here, a general relationship exists between the hypocentral volume and the downdip projection of the surface fault zone. The seismicity of the Mina region (M, Fig, 1; Fig. 2), however, contrasts with that of the rest of the belt, as described below.

The Mina region seems to have an epicenter density (1970–1972 data) equal to that of almost any other region of the seismic belt and has a b-value (0.93–1.06) that significantly exceeds the Nevada average (Ryall and Priestley, 1975). The Mina region. however, has had no comparable historic main shocks and has dispersed epicenters which do not line up with the locus of 1934 ground breakage on the Excelsior Mt. fault nor with any other known fault (Fig. 2). The formless pattern of epicenters of the western Mina region shown in Figure 2 is corroborated by earthquake ($M = 2–5$) data for 1970-1977 and microearthquake data for 1974–1977 of Van Wormer and Ryall (1979). These workers also indicated that focal depths are most commonly 5–15 km, occasionally up to 22 km, and that no obvious magnitude-depth relationship exists. Depth-magnitude relations for 29 microearthquakes in the Mina region studied by Gumper and Scholz (1971) are comparable. Composite focal mechanisms for earthquakes ($M \geq 2.5$) recorded in 1970–1972 and for 29 microearthquakes were prepared by Ryall and Priestly (1975) and Gumper and Scholz (1971). respectively. Both sets of investigators got similar and remarkably well ordered arrivals, although the data allow some latitude in choice of nodal planes (Fig. 3b).

Taken literally, the seismicity data for the western Mina region imply that at depths between about 5 and 15 km, frequent slips of small magnitude occur on faults that are more closely spaced than are the traces of main faults at the surface. The consistency of arrival field on the CFMS indicates that the distributed shears at depth have a highly restricted range of orientations. The most probable range of orientations of such shears, given the maximum elongation direction from surface faults and constraints of CFMS. is shown by the westish-striking nodal planes of Figure 3b (solid lines). Net slip directions allowed by such orientations are 1) left-oblique-normal for the dipping planes and 2) pure left slip for the vertical plane. Gumper and Scholz (1971) chose a modal plane close to those of Figure 3b to correspond with surface slip during the 1934 Excelsior Mts. earthquake.

Two interpretations are possible from these relationships: *1)* that earthquakes in the western Mina region represent slip on small shears that occur with equal frequency at all depths and are generally unrecognized at the surface; in this case, when a large earthquake occurs on a main fault with surface breakage, it will produce a colinear zone of aftershocks as elsewhere in the western seismic belt; and *2)* that the main faults at the surface splay with depth and transform down into a zone of more or less distributed shear. I favor the second idea because the *1934* earthquake (M = 6.3) on the Excelsior Mt. fault has no line up of aftershocks, and closely spaced shears, even of small displacement, should have been detected at the surface. If correct, it follows that displacement on the main left-oblique slip faults of the western Mina region may proceed without large earthquakes by upward coalescence of small slips from distributed shears at depth.

Ryall and Priestley *(1975)* interpreted the high recurrence rate of earthquakes in the western Mina region in the light of laboratory data to indicate that stress differences could attain only a moderate level because of a high degree of fracturing and high rate of strain release. I think we have arrived at comparable interpretations with different constraints.

Faulting in the seismic belt where the main breaks characteristically have northerly strikes apparently differs from that of the western Mina region in the following ways: *1)* seismicity is related to a more or less discrete displacement zone that extends to focal depths', *2)* widely distributed shear in an intermediate depth zone is either absent or suppressed, *3)* main fault zones can accumulate elastic strain sufficient to yield episodic 3 m displacements at the surface and $M \geq 7$ earthquakes, and *4)* the ratio of strike slip/dip slip is lower.

It would be interesting to compare the architecture with depth of these N-striking zones with that interpreted for the western Mina region. The Fairview Peak fault (F, Fig. *1)* which underwent seismic slip in *1954* ($M = 7.2$) has received considerable study. A dislocation model fit to the geodetic differences due to seismic and post-seismic slip (Savage and Hastie, 1969) suggests that a plane displacement zone would extend to at least 5 km at constant dip. A portable network study of aftershock hypocenters indicates that aftershock slips occurred in a zone at least *4* km wide between *5* and *15* km depth (Smith and others, *1972).* The hypocentral volume (dimensions greater than location uncertainties) lies generally downdip from the surface fault trace. CFMS for most of the aftershocks indicates that slip planes are oriented parallel to the main fault at the surface and the plane of the dislocation model. The aftershock pattern indicates that slips must have occurred on closely spaced en-echelon shears aligned parallel to and generally downdip from the shallow main fault (Smith and others, *1972).* Although it may be hazardous to estimate the depthwise structure of a fault zone by its aftershocks, the data permit the interpretation that the Fairview Peak fault splays with depth. Even so, the downward branching of the N-trending faults is nowhere as extensive as is apparently the case with faults of the western Mina region.

Figure 3c presents a conceptual model of the structure and displacement field of the Mina region; the model attempts to explain changes with depth and the west to east transition between E- and N-striking main faults. The plan view shows general westward (W to N80W) displacement and elongation and *a* major kink in fault traces through the Mina region. In the western domain, spaced inclined faults occur in a brittle upper layer ($\leq$ *5* km thick). These ramify downward into a zone of closely spaced faults between about *5* and *15-20* km depth. If.the faults are inclined to the north, the displacement in this intermediate layer can be accommodated entirely by shear with left-oblique normal slip; if the faults are vertical, however, one must appeal to stretching of intrafault foliae normal to the fault planes in addition to pure left slip on the faults. The intermediate zone **is** shown grading down to a wholly ductile zone. The upper brittle layer in the western domain does not undergo uniform elongation for various contrived reasons (variable strength, variable wall friction among blocks, nonuniform strain rate in layer below, etc.). Blocks in the upper layer move apart on surfaces favorably oriented for sliding compatible with the subjacent shear system.

In the eastern domain, the eesternmost fault (the Cedar Mts. zone) **is** shown to be a zigzag N-striking zone that is laterally continuous and has slight downward splaying toward the ductile region. It has, however, more of the character of a discrete displacement zone. In the transitional territory between the two domains, fault sets that cross blocks between the E-striking faults are more continuous to the east and progressively transform off more of the displacement on the E-striking faults.

The following rationale suggests that the seismic base of the Basin-Range fault zone in the Mina region is probably the transition depth to ductile flow in which only unusually rapid local flow could create a viscous earthquake. Given a surface heat flow of **1.8** hfu (corrected for modal Basin-Range radioactive heat production of a **10** km skin depth, Lachenbruch and Sass, **1979)** and assuming no convective transport in the upper **15** Ian, the steady state temperature gradient would be about 30°C/km. Thus, at the 15 km base of frequent hypocenters, T ~ 450°C. The transition depth from brittle failure to flow of, olivine (wet or dry) at 10^{-14} s^{-1} under the above temperature gradient is between **15** and **20** Ian according to Kirby **(1977).** However, the dry transition frictional shear stress induced by lithostatic load at these depths according to Byerlee (1968) would be **3.5** to ***4.5*** kbar! If pore pressure or extensional tectonic stress are added, the brittle zone will extend deeper but probably not as deep as 30 km where the shear required for the prescribed strain rate of olivine would be the order of 100 bar. **It is** reasonable to assume that the upper **15-20 km** are composed of material with a lower temperature brittle-ductile transition than olivine or dunite (Heard, **1976).** Given the wet solidus of granodiorite at about **20** Ian under this temperature gradient, a b-d transition at or above **20** Ian seems likely.

Experimental work supports the feasibility of the idea that fault zones ramify down toward **a** state of distributed shear with increasing lithostatic stress and temperature (e.g., Heard, **1976).** A physical rationale for the lateral change in fault behavior in the Mina region, however, is less evident. **It is** difficult to appeal to different thermal or fluid regimes because the depth interval of hypocenters **is** probably similar in the two domains. The most apparent explanation **is** that a pre-Basin-Range, E (or ENE-striking) planar fabric pervades the western Mina region (to **15-20 km)** such that shear stress resolved from regional extension finds a minimum of frictional resistance in that direction. **An** E-trending plate collision zone of Early Triassic age in the Mina region may account for the hypothesized planar fabric.

Some Possible Generalizations

The foregoing permits some speculative generalizations. Rheologically, the Great Basin is a three layer system of which the lowest is ductile and lies below about 15–20 km. The upper layer a) is $\geq$5 km thick, brittle, and comprised of blocks with characteristic dimensions of 5–10 km between fault boundaries. Motion in layer a) is chiefly on well defined steep fault surfaces which bound the blocks and consists of sliding induced by displacements in the intermediate layer. The main faults (i.e., principal displacement zones) in layer a) seem to be coplanar with subjacent slip surfaces. Moreover, they are probably unhealed. Thus, layer a) is apparently passive and generally aseismic, although block aotions are probably not independent and not uniform. The strikes of most main faults in layer a) are at high angles to the regional extension direction (which is convex to the west in the western Great Basin) and thus, such faults have displacements with dip slip/strike slip > 1. This geometric relation does not hold in the western Mina region (and perhaps other regions of the western Great Basin) where fault strikes are aligned near the extension direction and slip is prevailingly lateral. Such anomalies may be controlled by pre-Basin-Range fabrics in the intermediate layer.

The intermediate layer b) contains the transitional interval from ductile to perfectly brittle regimes and probably, from continuous and penetrative to heterogeneous and highly discrete displacement loci. Its depth interval, 5 to 15–20 km, contains most of the recorded hypocenters, and the kinematic behavior of layer b) must be inferred from its seismicity. Fault zones in layer b) which are at high angles to regional extension can accumulate sufficient elastic strain for large earthquakes. Aftershocks on such faults indicate distributed shear on parallel surfaces in a confined volume generally downdip or below the associated discrete fault in layer a). Where shear surfaces are at low angles to regional extension (western Mina region), slip is apparently more uniformly distributed in layer b). Here, the distributed shear surfaces coalesce upward in layer b) to discrete fault zones of layer a) and frequent and relatively easy failure prevents strain accumulation for large earthquakes.

Seismicity Variations and Topographic Stress

Analysis in progress indicates that seismicity (epicenter density, energy outflux) in the Great Basin is correlated with regionalized topographic slope (i.e., slopes at wave lengths $\geq$ 100 km). Such slopes are up to 0.3°, and associated shear stresses ($\tau = \rho g h \sin\alpha$ where a = slope, h = depth) are as great as 25 bars within layer b in the patterned regions of Figure 1. Thus, shear stress variations with this amplitude are sufficient to affect significantly the rate of seismic slip. The topographic stress is probably superposed on a more general inlayer extensional stress.

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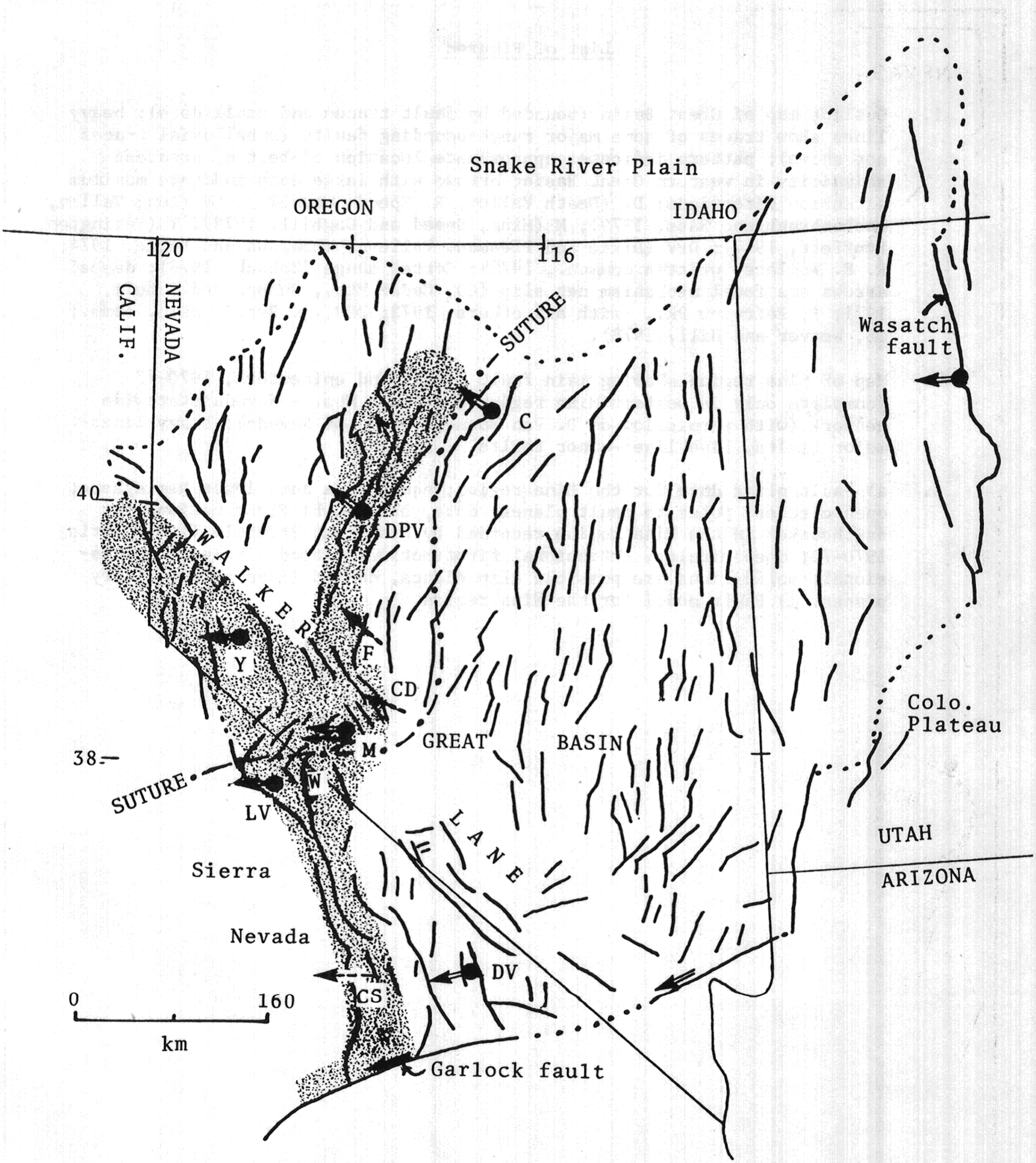
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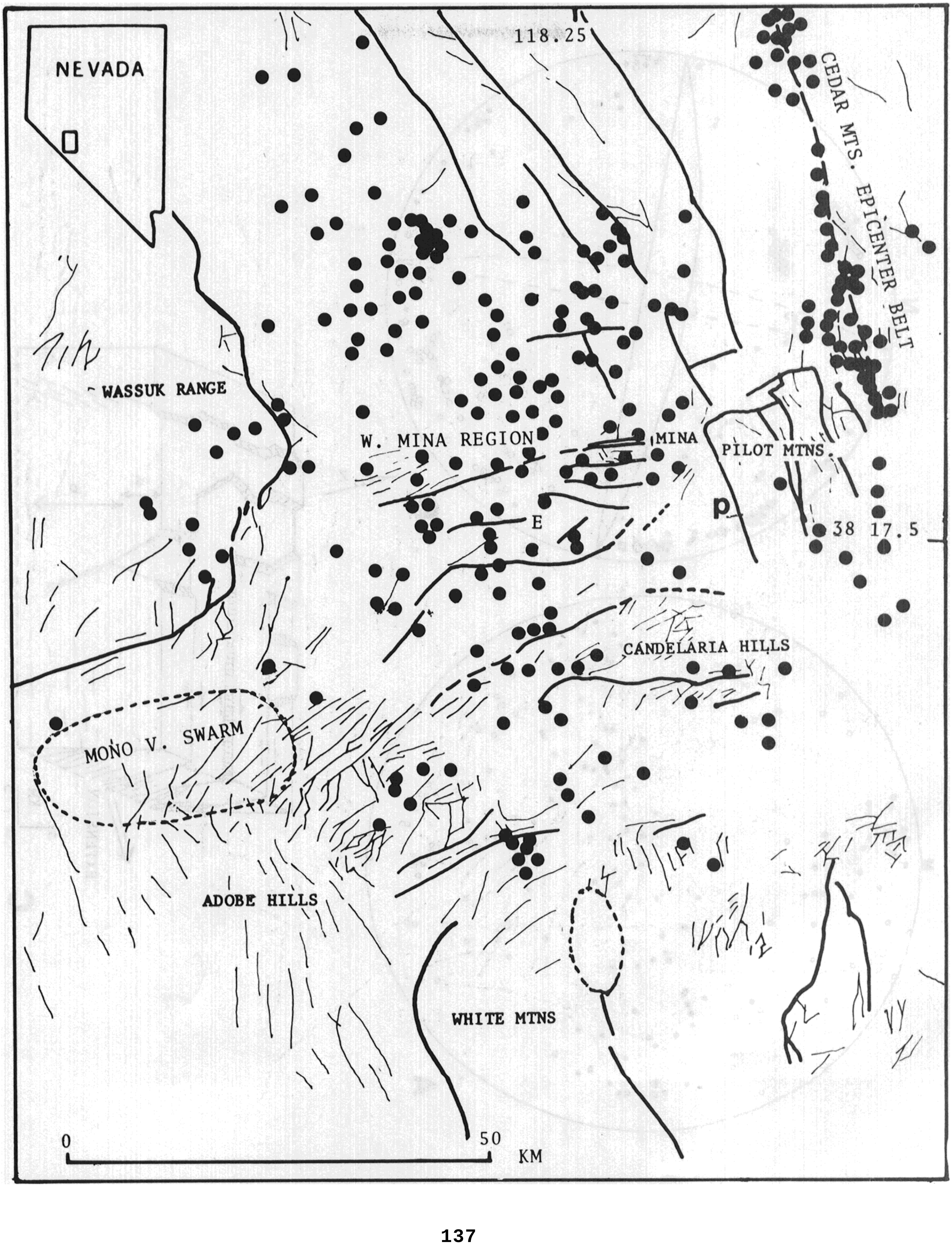
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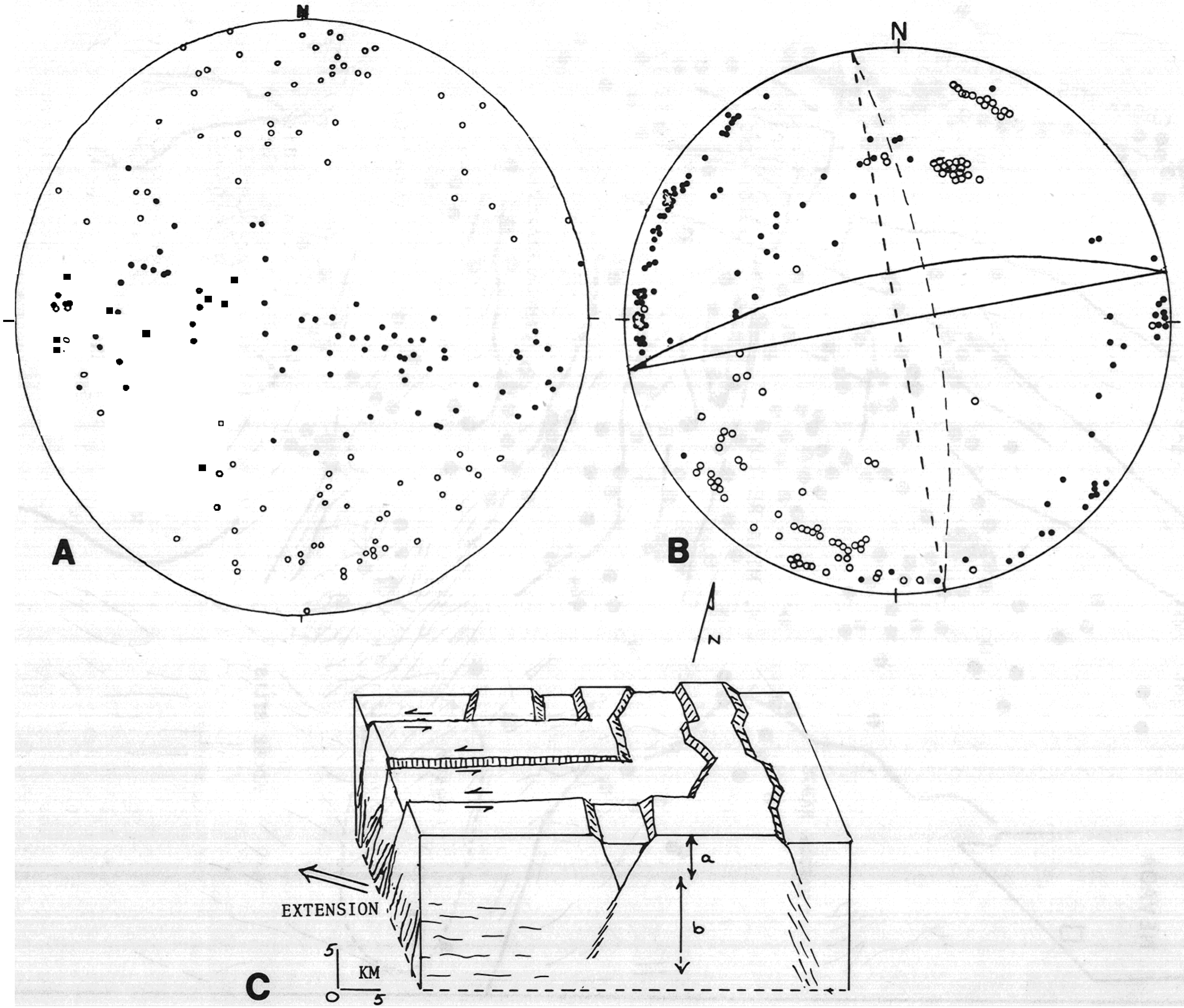
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