Magnitude of crustal extension in the southern Great Basin

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ABSTRACT

Strike-slip faults in the southern Great Basin separate areas of Cenozoic upper crustal extension from relatively stable tectonic blocks. Linear geologic features, offset along the Garlock fault, Las Vegas Valley shear zone, and Lake Mead fault system, allow reconstruction of the southern Great Basin to a pre-extension configuration. The Sierra Nevada, Mojave Desert, Spring Mountains, and Colorado Plateau are treated as stable, unextended blocks that have moved relative to each other in response to crustal extension, with the Spring Mountains held fixed to the Mojave block. Our reconstruction indicates a minimum of 65% extension (140 km) between the southern Sierra Nevada and Colorado Plateau.

INTRODUCTION

The amount that continental lithosphere may extend without (or prior to) the formation of oceanic lithosphere is of central importance to geodynamics, yet accurate determinations of large-scale intracontinental extension, constrained by several independent lines of evidence, are sparse. For example, the amount of Cenozoic extension in the Basin and Range province has traditionally been an extremely difficult quantity to constrain. Estimates of province-wide extension presented thus far in the literature range from 10% to 100% increase over original width, which corresponds to about 70 to 400 km of pull-apart in the northern Basin and Range province. Conservative estimates (10% to 30%) are based on assumptions of normal fault geometry in which stratal rotation is proportional to the amount of extension (Thompson, 1960). Assuming an average angle of 60° between faults and beds, the observed average tilt of 15° to 20° for late Cenozoic Basin and Range fault blocks led Stewart (1980) to deduce 20% to 30% extension for the entire province. It should be noted, however, that Stewart intended this estimate to apply only to extension related to the modern basins and ranges and not to events that predate their formation. Liberal estimates are based on three arguments. One is the relative crustal thicknesses between the Basin and Range province and the Sierran and Colorado Plateau provinces (Anderson, 1971b; Hamilton, 1978). Estimates ranging from 30% to 100% can be made if one assumes that the current 20 to 35 km Basin and Range crust was thinned from a crust as thick as the 40 to 50 km Colorado Plateau and Sierran crust. Unfortunately, actual crustal thickness in many areas of the Basin and Range is highly uncertain, and the pre-extension configuration of the Moho there can only be assumed. Another estimate is based on palinspastic restoration of Mesozoic paleotectonic elements of the Cordillera (Hamilton and Myers, 1966; Hamilton, 1969) which realigns the Sierran batholith and associated oceanic terranes with the Idaho batholith and oceanic terranes in western Idaho and eastern Oregon. This method yields roughly 50% to 100% extension for the northern Basin and Range province. A third estimate is based on the Cenozoic clockwise rotation of the western Cascades bracketed at 27° ± 7° by Magill and others (1981). They used a combination of paleomagnetic and geologic constraints to estimate 340 km (74%) extension in the northern Basin and Range and 210 km (140%) at the latitude of Las Vegas, Nevada. We feel that their analysis provides support in favor of a large amount of extension, but within the uncertainties of the constraints from which these figures were deduced, extension could have been as little as 210 km (36%) in the northern Basin and Range and 80 km (33%) at the latitude of Las Vegas. Problematically, Mankinen and Irwin (1982) and Craig (1981) have presented data that suggest smaller clockwise rotations of the Cascades (12° ± 11°) and Klamaths (12° ± 16°).

Perhaps the most accurate way of estimating extension is by restoring offset of linear geologic features across strike-slip faults that represent transformlike faults between areas of differential extension (Hamilton and Myers, 1966; Wright and Troxel, 1970) (Fig. 1). This method has been effectively used to quantitatively constrain minimum amounts of extension on a subregional scale (for example, Davis and Burchfiel, 1973; Guth, 1981). The favorable distribution of these structures across the southern Great Basin enables us to make an accurate minimum determination of extension across the entire province at the latitude of Las Vegas (Fig. 1A). Because this method is independent of assumptions implicit in the estimates based on normal fault geometry, large-scale paleogeography, crustal thickness, and paleomagnetic data, we feel that it provides an independent test of those estimates.

GARLOCK FAULT

Reconstruction of the western part of the transect is possible by matching correlative features across the Garlock fault. Left-lateral displacement on the Garlock fault, due to east-west extension in the Basin and Range province, appears to increase westward to a zone of maximum offset between the southern Sierra Nevada and the Mojave block (Hamilton and Myers, 1966; Troxel and others, 1972; Davis and Burchfiel, 1973). Correlation of the southern part of the Independence dike swarm north of the Garlock fault with dike swarms on the south side of the fault was first proposed by Smith (1962), who concluded that about 64 km of left-lateral offset had occurred since emplacement of the dikes in Mesozoic time (Fig. 1A). Smith and Ketner (1970) later proposed 48 to 64 km of left-lateral offset of the Paleozoic Garlock Formation. Finally, Davis and Burchfiel (1973) proposed that the Layton Well thrust, mapped by Smith and others (1968), is the offset equivalent of a thrust fault in the Granite Mountains 56 to 64 km to the east. These and other possible correlative features also discussed by Davis and Burchfiel (1973) constitute strong evidence for major left-lateral displacement.

Davis and Burchfiel (1973) proposed that the Garlock fault once continued at least 30 km to the east of its current surface termination at the southern Death Valley

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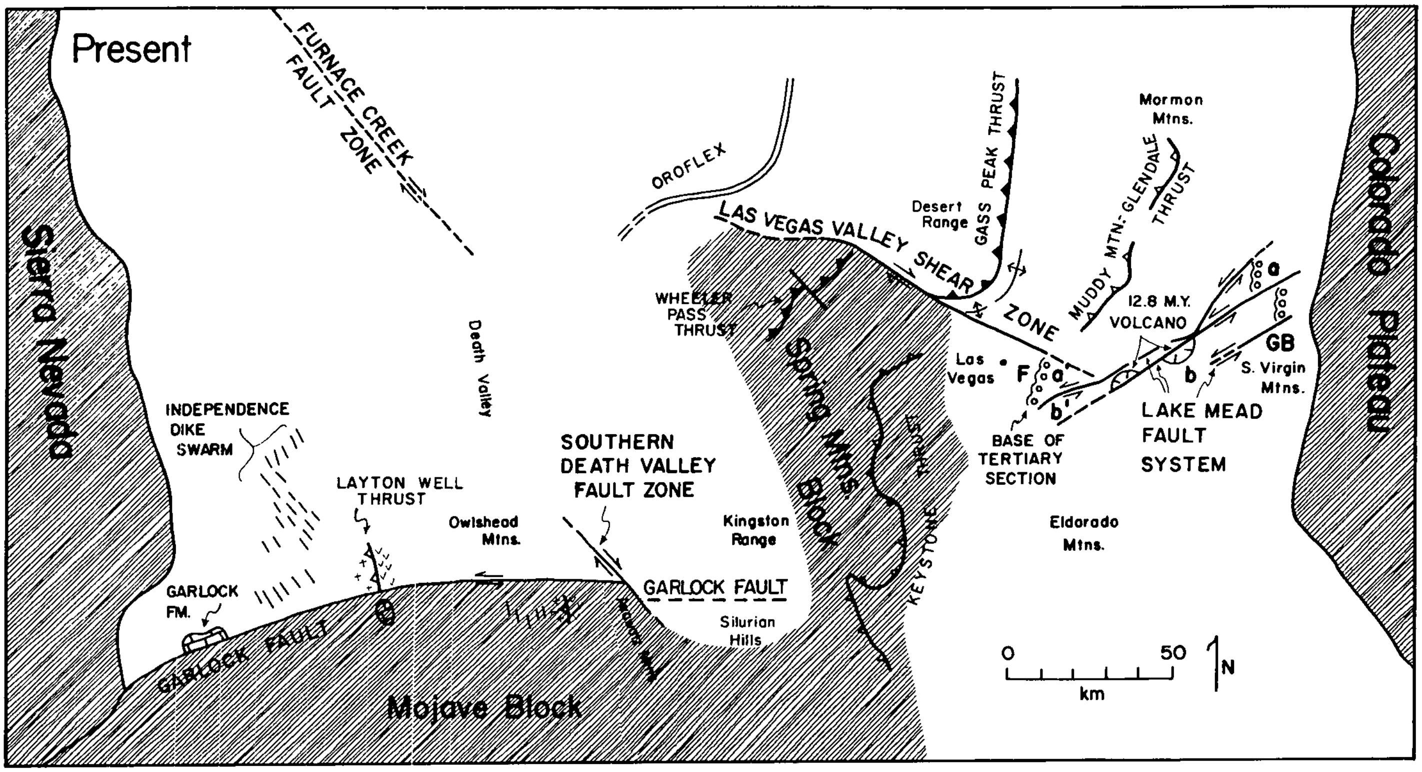
fault zone to a point of zero offset between the Kingston Range and Silurian Hills (Fig. 1A). According to this hypothesis, about 60 km of offset on the eastern Garlock fault was accommodated by extensional faulting across a terrane now 115 km wide. This terrane, encompassing the Owlshead Mountains, Kingston Range, and a broad, structurally complex intermediate area, must have undergone at least 100% extension. Recent unpublished mapping by Burchfiel and others has shown that the eastern part of the Kingston Range contains numerous low-angle normal faults and steeply tilted fault blocks, similar to the intermediate area (Wright and Troxel, 1973). Interestingly, the extended terrane ends to the south roughly along the eastward projection of the Garlock fault.

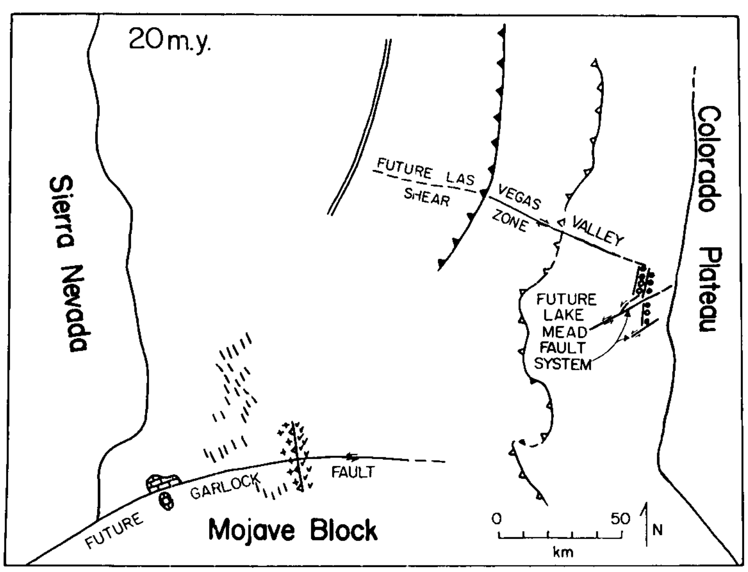
In Figure 1B, we have essentially followed the reconstruction of Davis and Burchfiel (1973), and we note that as long as crustal shortening south of the Garlock fault can be ruled out, our estimate of 60 km net crustal extension north of the Garlock fault is minimum.

LAS VEGAS VALLEY SHEAR ZONE AND LAKE MEAD FAULT SYSTEM

Reconstruction of the eastern part of the transect is made possible by matching features across the Las Vegas Valley shear zone and Lake Mead fault system (Fig. 1A). Right-lateral offset on the Las Vegas Valley shear zone was first postulated by Longwell (1960) on the basis of apparent eastward displacement of thrust faults that place Cambrian carbonates over Jurassic sandstones (Keystone–Muddy Mountain



A



B

Figure 1. A: Map of strike-slip faults and offset geologic features in transect extending from Colorado Plateau to Sierra Nevada. Shaded areas are assumed not to have undergone major extensional faulting; unshaded areas include both extended and stable terranes. Fault movements can generally be modeled as result of movement between Colorado Plateau, Sierra Nevada, and Mojave–Spring Mountains block. GB = Gold Butte, F = Frenchman Mountain. See text for discussion. B: Fault reconstruction based on offset features shown in A, indicating about 140 km of net pull-apart with a component of southward movement of Sierras with respect to Colorado Plateau. See text for discussion.

system). Burchfiel (1965) showed that the shear zone did not exist as a surface rupture west of the northernmost part of the Spring Mountains block but was instead expressed by large-scale bending (termed an "oroflex" by Albers, 1967), which gradually gave way eastward to a discrete fault zone. He strengthened Longwell's estimate of offset by correlating the Wheeler Pass thrust in the Spring Mountains with the Gass Peak thrust north of the shear zone, suggesting an offset of about 23 km by surface breaking beneath Las Vegas Valley and an additional 21 km by bending. To this figure, Longwell (1974) postulated an additional 25 km of right slip due to bending of the Wheeler Pass thrust from a north-south to northeast strike, as observed in the structural grain of two lower thrusts (Lee Canyon and Keystone) in the Spring Mountains. These data, in addition to stratigraphic data summarized in Stewart and others (1968), indicate total displacement in the range 44 to 69 km.

The transform character of the Las Vegas Valley shear zone envisioned by Davis and Burchfiel (1973) and Liggett and Childs (1974) was examined in detail by Guth (1981). He observed that oroflexural bending in the Specter Range area was not as great as the offset of the Gass Peak–Wheeler Pass thrust, and he suggested that this difference in offset could be accommodated by extension north of the shear zone. His hypothesis is strongly supported by the surface geology, in which few extensional structures can be found south of the shear zone in the Spring Mountains block, but a broad terrane of steeply tilted Paleozoic and Tertiary strata are offset along low-angle normal faults north of it (Longwell, 1945; Guth, 1981). Guth further noted that the spacing between the Gass Peak and Glendale thrusts north of the shear zone is nearly identical to that between the Wheeler Pass and Keystone thrust to the south. The areas between the faults both north and south of the shear zone are devoid of structures suggestive of significant Tertiary extension, thus supporting the transform concept and indicating that these areas behaved as stable blocks during extension.

Offset on the complex Lake Mead fault system was first noticed by Anderson (1973), who documented a 20 km left-lateral offset of the 12.7-m.y.-old Hamblin-Cleopatra stratovolcano by one fault of the system, and he speculated on roughly 65 km of total displacement. In a study of Tertiary sediments in the Lake Mead region, Bohannon (1979) provided firm support of about 65 km of left slip on the system as a whole, on the basis of remarkable similarity between Frenchman Mountain (location F, Fig. 1A) and the South Virgin Mountains. This similarity includes (1) a distinctive stratigraphic sequence at the base of the Tertiary section (locations a and a′ in Fig. 1A), (2) gradual southward pinchout of identical Mesozoic formations beneath the basal Tertiary unconformity, and (3) the presence f distinctive monolithologic breccia sheets of Gold Butte rapakivi granite (Anderson, 1973; Longwell, 1974; now exposed in bedrock only in the South Virgin Mountains, location GB, Fig. 1A) in the Tertiary section at Frenchman Mountain. Consistent with Bohannon's figure, Smith (1981) provided data in support of a 40 km offset for one strand of the Lake Mead fault system by correlating the River Mountains stock just southeast of Frenchman Mountain with a compositionally similar volcano-plutonic assemblage in the northern Black Mountains (b′ and b, respectively, in Fig. 1A).

DISCUSSION

Conservative reconstruction of offset features along the strike-slip faults yields a total pull-apart of 140 km for the transect (Fig. 1B), which corresponds to a 65% increase in original width. This figure is based on the assumption that areas on the "stable" side of the strike-slip faults have not also extended. However, Dokka (1981) has mapped an area in the Mojave block which shows extreme northeast-southwest upper crustal extension between 21 and 16 m.y. ago, although the Mojave block immediately south of the Garlock has been tectonically stable relative to Pliocene and Quaternary extension in the Death Valley area. The Silurian Hills (Kupfer, 1960; Fig. 1A), just south of the projected trace of the Garlock east of the Death Valley fault zone inferred from geophysical data (Plescia and Henyey, 1982), contains extensional structures similar to those in the highly extended Death Valley region and may possibly represent large-magnitude extension, although the terrane south of the Silurian Hills between the southern Avawatz Mountains and the Spring Mountains block does not contain any significant extensional structures (Burchfiel and Davis, 1971; DeWitt, 1980). In any event, there is no evidence of significant crustal shortening anywhere south of the Garlock during extension.

Other areas of possible extension not accounted for in the reconstruction include the region between the Independence dike swarm and the Sierra Nevada, possible minor extension in the northern Spring Mountains block, almost certain extension between the South Virgin Mountains and the Colorado Plateau (see cross section on p. 115 in Longwell, 1945).

Since the sources of uncertainty seem to have the effect of increasing the estimate, we believe that 140 km is a reasonable minimum figure, corresponding to an increase in original width of about 65%. In light of the uncertainties, it is possible that the total extension is in the neighborhood of 80% to 100%. We believe this result lends considerable credibility to the other lines of evidence discussed above that suggest Cenozoic extension of the Basin and Range province on the order of a factor of two, as first deduced by Hamilton and Myers (1966). According to our analysis, the approximately 30(+) km crust characteristic of our transect (Smith, 1979) was at least 45 to 50 km thick following the Mesozoic Sevier orogeny. The configuration of the Moho at that time may have been similar to the modern-day Andes, in which the crust thickens as one moves from the Brazilian Shield into the back-arc thrust belt (James, 1971).

Because the crust in the northern Basin and Range province is currently as thin or thinner than the crust in our transect and because large areas of the northern Basin and Range have been shown to exhibit the same structural style as highly extended areas in our transect (for example, Armstrong, 1972), we believe that it has undergone a similar amount of extension and regard 60% to 80% (300 to 500 km) increase in width as likely.

The data discussed here also support geophysical studies of continental rifting which have recently found that extension of the continental lithosphere by a factor of two without forming oceanic crust may be quite common (McKenzie, 1978). It is now the task of geologists studying well-exposed examples of severe continental pull-apart to develop models of the cross-section geometry of upper crustal extension which are consistent with that deduced by other means. The widespread occurrence of Tertiary younger-over-older low-angle fault terranes throughout the Basin and Range (Young, 1960; Wright and Troxel, 1973; Moores and others, 1968; Anderson, 1971a; Armstrong, 1972, among the early workers) is highly significant toward this development. The interpretation of these terranes as large, rooted low-angle normal fault complexes (Wernicke, 1981, 1982; Wernicke and Burchfiel, 1982) geometrically analogous to (but not necessarily a reactivation of) thin-skinned compressional belts is one means by which large-scale extension may be expressed in the surface geology. The existence of such complexes suggests that large horizontal translations of rock masses may occur without significant stratal rotation—that is, terranes regarded as "stable" in our reconstruction may be underlain by large low-angle normal faults.

Although our purpose here has been to place a lower limit on total extension in a straightforward manner using reliable data on the amount and direction of strike-slip offsets, we remind the reader that the less straightforward task of relating the timing and kinematics of individual extended terranes to the strike-slip faults still lies ahead and will provide a further test of the arguments presented here.

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